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Assessment of Ecosystem Services Bundles
Contribution to decision-making at city scale

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Assessment of Ecosystem Services Bundles: Contribution to decision-making at city scale.

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I dedicate this thesis to my late father, Ahmed Saïdi, whose legacy constitutes the foundation of any knowledge or skill demonstrated here.

Declaration

I, the candidate, hereby declare that this thesis is my own work and has not been submitted for any other higher degree. All references cited have been consulted unless otherwise stated.

Signed: Nada Saïdi

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Abstract

Ecosystems hold a crucial role in sustaining human life. However, societal decisions about the relative importance of different ecosystem services has led to intentional and unintentional trade-offs among them. This issue has prompted the emergence of an extensive field of research dedicated to the study of the interrelationships among ecosystem services. In this context, the identification and analysis of sets of ecosystem services consistently associated together across space and/or time - so-called "bundles" - has gained momentum as a robust approach to evidence and communicate trade-offs and synergies in various landscapes.

Approaches to identify and analyse bundles provide a statistically-backed and visual way to represent ecosystem services' associations: this has led researchers to stress their high potential to inform decision-making related to land-use planning and management. The realisation of this potential is however not straightforward, as the use of ecosystem services knowledge in decision-making involves complex processes and can take multiple forms. In this context, an in-depth analysis of the potential contributions of bundles is warranted, which explores their likely uses and the factors mediating them. I aimed, with this thesis, to provide such an analysis. The research reported here focuses on high-level decision-making at city scale, with the City of Edinburgh (UK) as a case study. It involves a spatial bundle assessment and a study of how the ecosystem services concept is integrated in policies and strategies.

Based on results in Edinburgh, I identify and describe uses for bundle assessments at city scale along three categories: conceptual, to raise awareness and reframe dialogues; strategic, to build support for plans or policies; and instrumental, to make specific

decisions. I first demonstrate that bundle results can raise awareness of the full range of nature's contributions in a city, by showing how lesser-known ecosystem services are associated with those traditionally included in policies and strategies. Bundle results can also help to address misconceptions about the co-occurrence of ecosystem services, as the policy discourse around nature's multiple benefits may not fully reflect patterns of ecosystem services provision. In addition to these two conceptual uses, bundle results can help to advocate for the protection of, and better access to, greenspaces of different sizes – as bundles provide evidence of benefits from both small and large greenspace. Last but not least, in addition to this strategic use, bundle results can be used instrumentally: the spatial patterns they evidence can help to prioritise areas for intervention, in a context where the uneven access to nature's benefits is a growing and global socio-environmental issue in cities.

In this thesis, I also argue that the effective use of bundle results in decision-making depends on their salience, credibility, and legitimacy. By identifying criteria along these three dimensions, I provide recommendations to researchers wishing to develop policy-relevant projects based on bundles: the conceptual, strategic, and instrumental uses outlined above, should provide ideas for such projects. In this regard, the thesis constitutes yet another step towards a better integration of ecosystem services assessments in decision-making.

Acronyms

AMM	Advanced Matrix Mapping
CART	Classification And Regression Tree
CICES	Common International Classification of Ecosystem Services
EDG	Edinburgh Design Guidance
EIJB	The Edinburgh Integration Joint Board
ELL	Edinburgh Living Landscape
ES	Ecosystem Services
GDPR	General Data Protection Regulation
GIS	Geographic Information System
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPBES	The International Panel on Biodiversity and Ecosystem Services
LBAP	Local Biodiversity Action Plan
LDP	Local Development Plan
MA	Millenium (Ecosystem) Assessment
MAD	Mean Around the Median

MCA	Multiple Correspondence Analysis
MDS	Multi-Dimensional Scaling
MLR	Multinomial Logistic Regression
NCP	Nature's Contributions to People
NHS	National Health Service
ONS	Office for National Statistics
OpenNESS	OPErationalisatioN of Natural capital and EcoSystem Services
OPERA	Operational Potential of Ecosystem Research Applications
OS	Ordnance Survey
OSS	Open Space Strategy
PAM	Partition Around Medoids
PCA	Principal Component Analysis
RGB	Red Blue Green
SBA	Service Benefiting Area
SDG	Sustainable Development Goals
SIMD	Scottish Index of Multiple Deprivation
SPU	Service Providing Unit
SuDS	Sustainable urban Drainage Systems

tb-PCA	transformation based PCA
TEEB	The Economics of Ecosystems and Biodiversity
UHI	Urban Heat Island
UK NEA	UK National Ecosystem Assessment
UN	United Nations

Chapter 1

Introduction

1.1 Introduction

Ecosystem services (ES) conceptualise the contribution of nature to people's quality of life: by providing an analytical perspective to the links between nature and society, the ES concept offers a framework for valuing these contributions (section 1.2.1). As a result, the past two decades have seen an increased interest in the potential of the concept to help develop and achieve sustainability goals; however, most land- and resource-use decisions still do not take ES into account (Posner, McKenzie & Ricketts 2016). This observation has led to recent reflexive work into the role of the ES concept, and associated knowledge, in decision-making processes (section 1.2.2).

In parallel, ES assessments have shown that the trend of increased provision of material ES, such as crops or timber, was happening at the expense of nature's ability to provide such ES in the future, and frequently undermining the provision of other types of services (Brondizio et al. 2019). These assessments have shed a light on the interrelated nature of ES across space and time, and on the adverse effects of current decisions - either intentional or not (section 1.2.3).

Within the extensive literature on the interrelationships among ES, Raudsepp-Hearne et al. (2010) were the first to identify consistent ES associations using statistical clustering techniques, an approach they called "bundling". Their seminal study led to further research identifying and analysing bundles of ES in different landscapes, at different scales, from diverse perspectives, and using various statistical methods (Saidi & Spray 2018). This bundle literature allowed the uncovering of a variety of trade-offs and synergies among ES, which has prompted many authors to highlight the potential of bundle identification and analysis to inform decision-making (sections 1.2.4 and 1.2.5).

However, no in-depth analysis of the potential contribution of bundles in decision-making has been conducted to date. This thesis aims to address this gap, building on research on ES associations and utilisation of ES knowledge in decision-making (section 1.3). It takes a case study approach and explores the potential contribution of bundles in an urban context, the City of Edinburgh.

1.2 Background

1.2.1 Ecosystem services: conceptualising the contributions of nature to people

Ecosystems and their associated ecological and evolutionary processes contribute, positively or negatively, to people's quality of life (Díaz et al. 2018). Although the beneficial or detrimental nature of these contributions depends on spatial, temporal, social and / or cultural context, they hold a crucially positive role in sustaining human life on Earth.

The ES concept is one of the perspectives developed to generate, analyse and communicate knowledge on the contributions of nature to human life. It gained prominence in the late 1990s and early 2000s with the work of Costanza et al. (1997) and the Millenium Ecosystem Assessment (MA) (MEA 2005). In particular, the MA mainstreamed the ES concept at the science-policy interface by using it to synthesise then-available knowledge on the condition and trends of the world's ecosystems. The

MA and later high-profile initiatives, such as The Economics of Ecosystems and Biodiversity (TEEB) and the UK National Ecosystem Assessment (UK NEA), conceptualised ES as services flowing from nature to people, mediated by the conditions and processes of ecosystems as well as human agency, and leading to benefits that can be valued (the so-called 'cascade model' introduced in Potschin & Haines-Young (2011)). This perspective has been challenged in some instances by empirical and conceptual developments in ecological, social and anthropological sciences, coupled with a greater integration of the social sciences and humanities in the study of nature-human relations (Faith 2018). As a result, the ES field has grown to include a diversity of value systems and perspectives, from viewing humans and nature as distinct entities (e.g. in a Natural Capital approach) to considering them as interwoven in deep relationships of kinship and reciprocal obligations (e.g. in Indigenous people communities) (Díaz et al. 2018).

To reflect developments in the ES field and the perspectives of a variety of stakeholders, including governmental and non-governmental organisations, Indigenous peoples, and local communities, recent conceptualisation efforts at the United Nations (UN) level have led to the emergence of the concept of "Nature's Contributions to People" (NCPs) (Díaz et al. 2015). The International Panel on Biodiversity and Ecosystem Services (IPBES) intends, with the NCP concept, to better include diverse perspectives and appeal to stakeholders who have had reservations about the initial framing of the ES concept (Brondizio et al. 2019). The NCP concept does not invalidate or exclude the ES concept; rather, it recognises it as the lens through which some communities of practice, including academia and European and North American policymakers, have been seeing the relationships between nature and people – a perspective which has been dominated by the idea of nature as a 'stock' or 'capital' from which services flow. In this thesis, I wish to reflect the most recent science-policy agreements at the international level, by adopting the categorisation used in IPBES work instead of the MA-based ones used by many in the literature up until recently. The IPBES categorisation was developed from pre-existing classifications (such as the ones of the MA and the Common International Classification of Ecosystem Services CICES) and validated by the international scientific and policymaking communities at its Seventh Plenary. It relies on three partially overlapping groups (Díaz et al. 2018):

- **Material ES** are substances, objects or other material elements from nature that directly sustain people's physical existence and material assets: examples include food, materials for construction or biomass-based fuels. They mainly refer to what has been called "provisioning ES" in previous classifications (Figure 1.1);

- **Non-material ES** are nature's effects on subjective or psychological aspects underpinning people's quality of life, both individually and collectively: examples include aesthetic enjoyment, learning or developing a sense of place. They mainly refer to what has been called "cultural ES" in previous classifications (Figure 1.1); and

- **Regulating ES** are functional and structural aspects of organisms and ecosystems that modify environmental conditions experienced by people, and/or regulate the generation of material and non-material contributions: examples include habitat creation, pollination or the regulation of freshwater quantity, location and timing.

This categorisation is heavily based on the MA and UK NEA classifications but differs on two key aspects (Figure 1.1):

- The MA introduced a class of "supporting services", which was meant to be used to categorise and highlight the importance of ecosystem functions and processes underpinning all other services. However, as noted by W. Reid and HA Mooney (respectively MA director and co-chair) in their reflection on the MA in 2016, the "supporting services" label, as opposed to alternatives such as 'supporting ecosystem functioning' or 'supporting of services' have led to misinterpretation by some, mainly economists fearing double counting in economic assessments (Reid & Mooney 2016). More generally, supporting services have been understood as "intermediate services" and often undervalued (Sutherland et al. 2018). Following the current view of those who led the MA assessment, as exemplified in Reid & Mooney (2016), supporting services have been reclassified as components of nature or as regulating services.

- A "cultural services" category has been used in various classifications to describe non-material benefits obtained from ecosystems. However, the implication that some services are cultural, and other are not, has been challenged by insights from the social sciences and the humanities: because it influences the perception and valuation of all ES, culture has been considered as a crucial lens through which they should be understood and analysed, rather than a separate category (Chan et al. 2006). The case of the "food" ES is a telling example of the importance of culture in analysing services: although mainly a material ES, its perception beyond sustenance varies depending on socio-cultural contexts, and along with it, its non-material contribution to human life. More generally, material and non-material ES are increasingly recognised as intertwined, with increasing evidence that people perceive them as "bundles" mediated by social, economic and cultural factors (Martin-Lopez et al. 2012, Hicks & Cinner 2014).

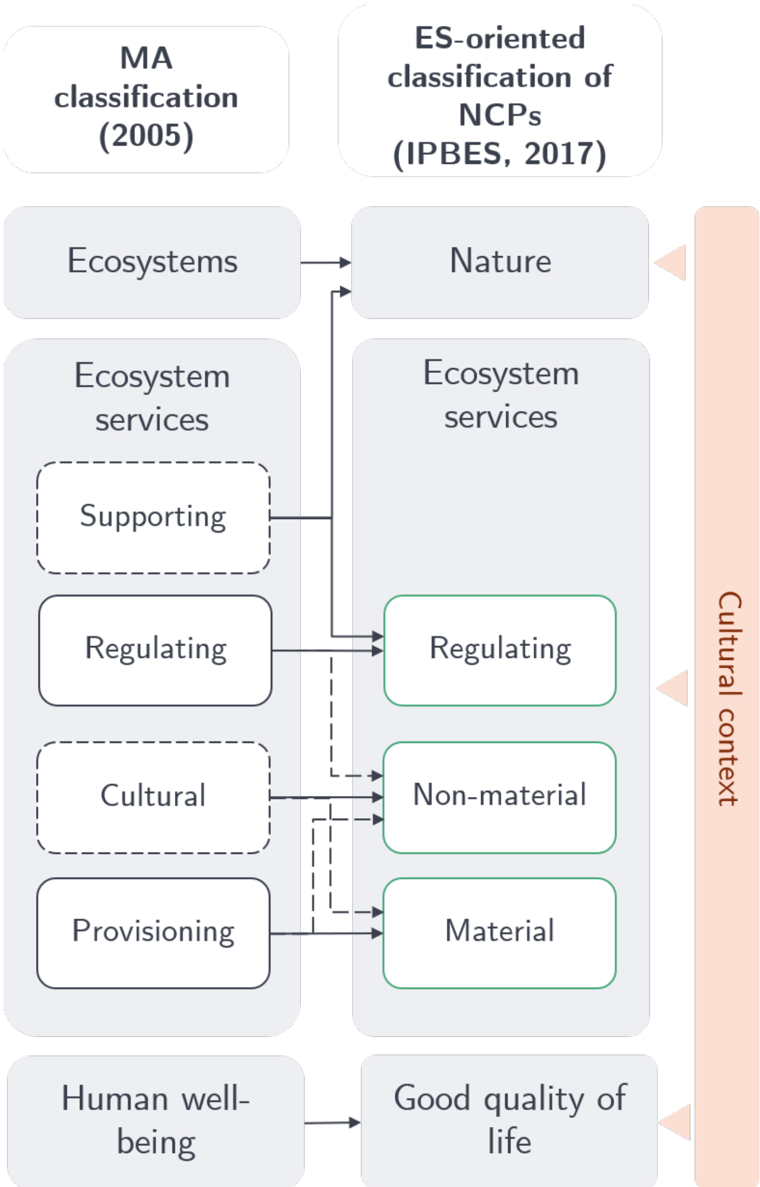


Figure 1.1: Links between ES categories from the first to the second global assessment of the state of biodiversity and ecosystem services, viewed from the ES perspective on NCPs. Dotted boxes indicate categories that have been replaced by an updated terminology. The dotted lines and the orange box show that the cultural context infuses the representation of the different categories: regulating, material and non-material. Modified from Díaz et al. (2018) to only include the ES-oriented classification of NCPs.

Beyond providing an analytical perspective on the links between nature and people, the value of the ES concept also resides in its ability to integrate diverse perspectives and forms of knowledge across social groups and organisational scales (Schleyer et al. 2017, Steger et al. 2018). This role of ES as boundary objects makes them a potentially powerful tool in a decision-making context (Steger et al. 2018).

1.2.2 Ecosystem services and decision-making

1.2.2.1 Salient, credible, and legitimate knowledge

The ES concept offers a framework where decision-makers and different scientific disciplines can be brought together to shape and achieve sustainability goals (Abson et al. 2014, Reyers et al. 2010). Some have argued that the ES concept, and more specifically knowledge generated by research on ES (thereafter called "ES knowledge"), could become a strong guide for natural resource management, poverty reduction and economic development (Keenan et al. 2019, Cook & Spray 2012). However, until recently, there has been a paucity of evidence about the role ES knowledge actually plays in decision-making (its "operationalisation"), and which factors facilitate its use (Jacobs et al. 2016, Dick et al. 2018). This is gradually changing with the publication of reflexive studies conceptualising and assessing how ES knowledge and decision-making interact (for instance Posner, Getz & Ricketts (2016), Mckenzie et al. (2014), Dick et al. (2018), Keenan et al. (2019), Brunet et al. (2018), Sarkki et al. (2014)).

These studies challenge the traditional view that knowledge should be speaking 'truth' to power; a view which assumes a linear one-way relationship between ES knowledge and policy, where policy makers pose well-defined questions, scientists provide knowledge, and policymakers will go on to develop solutions based on this knowledge.

Rather, empirical evidence shows that the processes of production, communication, and use of ES knowledge result from complex and multidirectional relationships between scientists, decision-makers, and other stakeholders. Reflexive studies on the use of ES knowledge argue that three attributes of knowledge production and exchange – salience, credibility and legitimacy– together promote effectivity and explain outcomes regarding the production, communication, and use of ES knowledge (Cash et al. 2003, Cook et al. 2013):

- Salience: relevance to the needs of decision-makers and delivery in the right timing;
- Credibility: reliability and trustworthiness of the scientific evidence and arguments;
- Legitimacy: inclusion of diverse values enabled by an unbiased and fair process of knowledge production.

These studies also argue that knowledge is something better understood as socially constructed (co-production) (Young et al. 2014, Cash et al. 2006), especially in the field of biodiversity and ecosystem services, where uncertainties are high and values contested. As a result, processes of interactions among researchers, decision-makers, and other stakeholders, as well as contextual conditions regarding governance systems and institutional capacity, are two additional determinants of the effective use of ES knowledge in decision-making.

These factors are interrelated. The attributes of ES knowledge enabling its use are often connected to their ability to engage all stakeholders in a collaborative process where mutual learning and knowledge co-production is encouraged (Mckenzie et al. 2014, Brunet et al. 2018, Dick et al. 2018). Credible ES knowledge builds trust between researchers and decision-makers, while its salience favours engagement and awareness-raising, both of which are important elements in developing transparent collaborative processes. Conversely, interactive processes of knowledge production enhance the credibility and salience of ES knowledge jointly produced by the different stakeholders, such as maps, models, scenarios and tools (Ruckelshaus et al. 2015). They also ensure the legitimacy of this knowledge. Legitimacy is crucial in enabling change at all stages of the decision-making process, including in the later stages where ES knowledge is integrated in the decision outcomes: then, the perception of knowledge production as an unbiased process, integrative of diverse values, is more important than knowledge credibility (Posner, McKenzie & Ricketts 2016, Brunet et al. 2018). The development of such interactive processes is in part enabled by researchers, but also relies on the capacity of governance systems and institutions to provide the necessary level of leadership, infrastructure, skills, legal framework, and incentives. Therefore, contextual conditions play a non-negligible role in the success of ES projects (Keenan et al. 2019).

Nevertheless, there are also important trade-offs in producing ES knowledge that is simultaneously salient, credible, and legitimate (Sarkki et al. 2014). For instance, the will to enhance the salience of knowledge by presenting simple and strong messages, may come at the expense of its credibility and legitimacy, by overlooking the various uncertainties and diverse values associated with it. Conversely, reporting uncertainties and exploring diverse options thoroughly and fairly, i.e. enhancing the credibility and legitimacy of knowledge, may decrease its salience by introducing too much complexity ('clarity-complexity' trade-off). Furthermore, efforts towards credibility and legitimacy, such as conducting quality assessments and building consensus, are time-consuming processes which may not enable the provision of rapid responses to decision-makers' needs ('speed-quality' trade-off). Finally, focusing on decision-makers' needs to produce demand-driven – salient – ES knowledge, may happen at the expense of ensuring credibility through independence ('push-pull' trade-off).

The severity of these trade-offs and the strategies through which they can be managed, depend on the phase of the policy cycle at which knowledge is produced or used; on the extent to which knowledge is or can indeed be co-created; and on how 'knowledge use' is understood.

The next subsection introduces the different types of uses associated with ES knowledge and discusses briefly how they relate to the trade-offs between salience, credibility and legitimacy.

1.2.2.2 Types of uses for ES knowledge

Based on seminal work by Weiss (1979) and Landry et al. (2001), who conceptualised the different modes of research utilisation, recent literature on the operationalisation of ES has identified three main types of use of ES knowledge (for instance Posner, Getz & Ricketts (2016), Mckenzie et al. (2014), Dick et al. (2018)): instrumental, conceptual, and strategic. They are introduced and described in the following paragraphs.

Many ES studies or assessments seek or expect an *instrumental use* of the knowledge they produce, whereby decision-makers such as policymakers or urban planners are assumed to apply the results of ES research directly to generate a solution to a particular problem, to select among alternative policy or management options, or to develop and implement policy and finance mechanisms (Mckenzie et al. 2014, Waylen & Young 2014). However, recent literature suggests that, despite a number of projects and toolkits aimed at integrating ES into decision-making, assessments rarely play an instrumental role in influencing decisions (Ainscough et al. 2019). However, not achieving instrumental use does not mean that ES knowledge has not been used at all. Because decisions are often developed through interactions among different interest groups (Reed et al. 2010, Rosenthal et al. 2014), ES knowledge can also contribute to the decision-making process by influencing the way different actors think about the issue at hand. This process, called *conceptual use*, refers to a more general and indirect form of enlightenment than its instrumental counterpart – it may involve raising awareness about ES or enabling communication between stakeholders. ES knowledge can also be used to lend weight to pre-existing preferences and values, thereby enabling one or more stakeholders to *strategically use* this knowledge in the decision-making process.

There is a potential conflict between those who see ES as a tool for raising awareness and discussion (conceptual uses), and those who wish to see it directly used in decision-making (instrumental uses); however, as argued by Ainscough et al. (2019), the ES concept can play multiple roles at once. Indeed, studies which have investigated the impact of ES knowledge in transdisciplinary projects provide empirical evidence of all three types of use. Conceptual use is more prevalent and tends to occur early in the science-to-decision cycle: ES knowledge is used to raise awareness and to enable collaboration among stakeholders by applying a common understanding of the issue at hand (Mckenzie et al. 2014). At this stage, decision-makers may prefer complexity and uncertainty over a definitive message, especially when emerging issues are discussed – in that case, trade-offs between salience and credibility are effectively minimised (Sarkki et al. 2014). It also worth noting that the conceptual influence of ES knowledge can persist beyond the context in which it was generated, for instance by helping redefine the vision around the development of a region after an ES project is completed there (Dick et al. 2018). Strategic use of ES knowledge has been reported across various stages of the science-to-decision cycle, where stakeholders use ES knowledge to express their values and build support for their positions (Mckenzie et al. 2014, Posner, McKenzie & Ricketts 2016). Seeking strategic use may translate into an oversimplification of ES knowledge, so that the salience of this knowledge comes directly at the expense of its credibility, and possibly legitimacy. Finally, instrumental uses of ES knowledge often take time to occur, as a change in action often results from an incremental process involving conceptual and strategic uses of ES knowledge (Mckenzie et al. 2014, Dick et al. 2018).

1.2.3 Interrelationships among multiple ecosystem services

Global ES assessments have highlighted that more material ES are now being produced than ever before, increasingly at the expense of nature's ability to provide such ES in the future, and frequently undermining non-material and regulating ES (MEA 2005, Brondizio et al. 2019). These trade-offs have been happening because ES are often not independent from one another, and therefore not all interrelated services can be maximised simultaneously (Bennett et al. 2009, Howe et al. 2014, Lee & Lautenbach 2016, Plieninger et al. 2013). As a result, societies must make decisions about their relative preferences for different services: often, these decisions have been driven by single objectives, such as increasing crop production or carbon sequestration, without accounting for consequences on other ES or on the distribution of their benefits across stakeholder groups (Lester et al. 2013, Mouchet et al. 2017, Howe et al. 2014). While the resulting trade-offs are in some cases deliberate, they are also found to be unintentional, resulting from a lack of understanding of the complex interrelationships among ES across space and time (Tallis & Polasky 2011, Rodriguez et al. 2006).

This observation has led to an extensive field of research dedicated to the study of interrelationships among ES (Cord et al. 2017, Plieninger et al. 2013). In this thesis, the term "interrelationships" is an umbrella for both ES interactions and ES associations, following the distinction introduced by Bennett et al. (2009) and the terminology proposed by Vallet et al. (2018): ES interactions describe causal relationships among ES, while ES associations describe correlations due to common biophysical, socio-economic or institutional drivers. ES interrelationships have been found to take the form of trade-offs, synergies (i.e. positive interactions or associations) or "no-effects" (when ES are independent from one another) (Lee & Lautenbach 2016, Cord et al. 2017). These interrelationships are complex, as their strength and direction may change in space and time, potentially in a non-linear manner (Howe et al. 2014, Lee & Lautenbach 2016). This complexity means that the analysis of ES interrelationships remains a challenge, even though knowledge about them has been increasing (Plieninger et al. 2013). Crucially, there is a growing recognition that if knowledge on ES interrelationships is to be used to avoid trade-offs or promote synergies, then an in-depth understanding of their drivers is necessary (Dade et al. 2019, Spake et al. 2017, Chen et al. 2020). However, the relative importance of different biophysical, socio-economic and institutional drivers of sets of ES remains unclear

(Spake et al. 2017, Beninde et al. 2015).

Raudsepp-Hearne et al. (2010) were the first to highlight the need to distinguish between context-specific interrelationships and consistent ones across space and time. They introduced the identification and analysis of so-called "bundles of ES" as an approach to explore consistent ES associations and their drivers: this approach has been gaining momentum as a robust way to study ES associations in different settings (Saidi & Spray 2018).

1.2.4 Bundles: evidencing consistent associations among multiple ES

1.2.4.1 Definition, identification and analysis of bundles

Bundles can be defined as sets of ES which are repeatedly appearing together across space or time (Raudsepp-Hearne et al. 2010, Saidi & Spray 2018). They can be categorised into three types:

- 'ES bundles' identify groups of ES consistently appearing together;
- 'Spatial Bundles' identify groups of spatial units with a consistent similar ES profile; and
- 'Perception Bundles' identify groups of stakeholders with consistent similar ES perceptions.

A bundling approach consists in detecting and analysing patterns in a multivariate dataset of ES values: these values may either be spatially-explicit, i.e. reported for a set of spatial units, or they may correspond to a quantification of perceptions expressed by a set of individuals. In a matrixial representation of such a dataset, ES are the variables (columns) and spatial units / individuals are the observations (rows).

a. Identification of bundles

Identifying 'ES bundles' refers to the broader statistical problem of detecting clusters of variables within a multivariate dataset. The most common strategy, in general and in bundles studies, is to project the data onto a small number of dimensions preserving their multivariate structure as fully as possible (ordination in reduced space) (Everitt 2011, Saidi & Spray 2018). Groups of variables – i.e. ES bundles – are then identified graphically or tabularly in the reduced dimensional space. In bundle studies reviewed in Saidi & Spray (2018), ES datasets are mainly projected using Principal Component Analysis (PCA) (Bai et al. 2011, Turner et al. 2014, Depellegrin et al. 2016). Other techniques used are factor analysis (Qiu & Turner 2013), Multiple Correspondence Analysis (MCA) (Garcia-Nieto et al. 2013) and multidimensional scaling (MDS) (Riechers et al. 2017). ES bundles are visualised graphically or tabularly.

Identifying 'Spatial Bundles' and 'Perception Bundles' refers to the broader statistical problem of detecting clusters of observations within a multivariate dataset. In the following description, only the 'Spatial Bundles' type is described – challenges specific to Perception Bundles can be found in Saidi & Spray (2018). In general and in spatial bundle literature, the problem of detecting clusters of observations is commonly addressed using hierarchical or centre-based clustering analyses, which look to minimise the dissimilarity among spatial units belonging to the same group: close to 80% of spatial studies reviewed in Saidi & Spray (2018) use such methods, detailed in Chapter 2. Other techniques include self-organising maps (Crouzat et al. 2015, Dittrich et al. 2017), multivariate regression trees (Lamy et al. 2016) and PCA (Ryschawy et al. 2017). Spatial Bundles are visualised graphically with diagrams showing the ES profile of each cluster of spatial units – they are also represented in maps where all spatial units belonging to the same bundle are shown in the same colour.

The strategies governing the application of ordination or clustering methods for bundling mainly depend on the structure of the dataset, including the number of ES and the skewness of their distribution Saidi & Spray (2018). Nevertheless, very few studies justify their choice of ordination or clustering method; in particular, it is not clear how authors verify assumptions underlying the use of some methods, or how the structure of their data influences the interpretation of the identified bundles. Furthermore, *a posteriori* assessments of how well ES or spatial units have been bundled - i.e. the extent to which bundle identification is meaningful – has been, in these early days, the exception rather than the norm.

b. Analysis of bundles

The study of synergies and trade-offs often go beyond the identification of bundles. Additional analyses such as the detection of pair-wise associations, for instance by performing Pearson's or Spearman's correlation tests, are useful to understand the strength of trade-offs or synergies within a bundle or between bundles (Birkhofer et al. 2018, Depellegrin et al. 2016, Kong et al. 2018, Yao et al. 2016)). Another practice is to analyse ES richness or diversity with techniques such as overlap analysis or evaluation of the Simpson's diversity index (Lin et al. 2018, Marsboom et al. 2018, Renard et al. 2015).

In addition to these supporting analyses, identifying drivers for bundle formation has been a major feature in bundle-based studies of trade-offs and synergies (Spake et al. 2017). It has been done both qualitatively and quantitatively across the literature. Qualitative interpretation involves understanding where in a landscape trade-offs and synergies are the strongest, generally using interpretation of PCA axes and scores (Balzan et al. 2018, Hanspach et al. 2014, Queiroz et al. 2015). Nevertheless, only quantitative methods such as canonical analyses or regression models have the ability to robustly identify drivers for bundles. Whereas qualitative methods are exploratory, quantitative methods rely on the identification of candidate social-ecological variables that are important in explaining or predicting different bundles of ES at a specific scale (Rositano et al. 2018, Schulze et al. 2016, Lamy et al. 2016). This initial selection is based either on relationships demonstrated in the primary literature or on expert knowledge.

1.2.4.2 ES trade-offs and synergies evidenced by bundle studies

The identification and analysis of bundles is a flexible approach: it has been used to address a variety of objectives under the common goal of studying ES associations, and has been embedded in various methodological designs. Tables 1.1 and 1.2 present a categorisation of bundle studies based on the different types of objectives and methodologies identified in the systematic review conducted by Saidi & Spray (2018) (see below).

Table 1.1: Typology of bundle studies according to their objective.

Type of objectives	Description
Exploring ecosystem services patterns	They focus on discovering how ES are associated with each other (either biophysically or socio-culturally). Although this is an underlying goal for all reviewed studies, those that fall into this category do not state any other aim than advancing knowledge on ES associations. In these studies, the link to decision-making remains implicit. All types of methodological designs (see next Table) are represented.
Informing landscape management	Biophysical studies falling into this category identify bundles to support decision-makers in developing management strategies to ensure sustainable resource consumption. The assumption is that bundles can help by delineating different socio-ecological systems for which different types of interventions should be implemented. Socio-cultural studies falling into this category identify preferences bundles in the aim to include the potentially different demands from different stakeholder groups in landscape management. Studies falling under this goal were either mapping or preference assessments.
Studying the influence of land-use decisions	Studies interested in understanding the impact of current land use or of land-use scenarios on the distribution of ES. They either directly use bundles to show the differences in ES patterns or they identify land-use related drivers for previously delineated bundles. In the review, they were either mapping or experimental studies.
Addressing methodological challenges	Studies focused on methodological issues around identifying bundles in spatially-explicit assessment (scale and quantification methods).

Table 1.2: Typology of bundle studies according to their methodological orientation.

Type of methodology	Description
Mapping studies	They quantify the selected ES spatially—the quantification can be either biophysical or based on public participation. The resulting bundles may be represented spatially, although it is not always the case. This type represents more that 70% of studies reviewed in Saidi & Spray (2018).
Experimental studies	They try to identify bundles across separate locations, selected to control for predefined parameters. For instance, Birkhofer et al. (2018) studied ecosystem services interactions across 33 farms in a Swedish province, which were selected along a pre-defined complexity gradient in order to understand the influence of land-use complexity in the formation of bundles. The main objective of experimental studies is to identify bundles across different types of land-use or management decisions.
Preference assessments	They quantify the sociocultural value of the selected ES through surveys or semi-structured interviews. The type of population sampled and the size of the sample depends on the overall aim of the study. All socio-cultural valuations that are non-spatially explicit are placed in this category.

Bundles have been identified globally in different types of landscapes, which strongly suggests that ES do not appear randomly (Saidi & Spray 2018). Rich evidence has been brought from the biophysical and the socio-cultural perspectives.

From a biophysical perspective, bundles have shown both consistent trade-offs and consistent synergies. Trade-offs have been identified between material ES and regulating ES, a trend which had been suggested by the study of pair-wise associations (Lee & Lautenbach 2016). High levels of crop production are often associated with low levels of regulating and non-material services (Raudsepp-Hearne et al. 2010, Maes et al. 2012, Yang et al. 2015, Baro et al. 2017), especially water quality (Qiu & Turner 2013, Crouzat et al. 2015). These trade-offs show as 'specialised bundles' (Raudsepp-Hearne et al. 2010, Queiroz et al. 2015, Renard et al. 2015), which are characterised by the domination of one or two material ES (Raudsepp-Hearne et al. 2010, Turner et al. 2014, Dittrich et al. 2017, Lin et al. 2018, Qiao et al. 2018) – although the magnitude of trade-offs differs across studies.

Synergies identified from a biophysical perspective seem to appear only among non-material ES, and between regulating and non-material ES (Raudsepp-Hearne et al. 2010, Maes et al. 2012, Qiu & Turner 2013, Yang et al. 2015, Baro et al. 2017, Mouchet et al. 2017, Vigl et al. 2017). Some have hypothesised the interlinked, holistic nature of non-material ES from their simultaneous supply in various landscapes (Plieninger et al. 2013), in particular in urban and peri-urban areas (Turner et al. 2014, Queiroz et al. 2015, Baro et al. 2017). Synergies have also been found among regulating ES, primarily in forested areas (Maes et al. 2012, Qiu & Turner 2013, Mouchet et al. 2017, Kong et al. 2018); however, nutrient regulation and carbon sequestration were negatively associated in two studies (Bai et al. 2011, Alamgir et al. 2016). Additionally, a few studies have shown that some areas are characterised by a mixed provision of ES, i.e. medium to high levels of a high number of services (Raudsepp-Hearne et al. 2010, Turner et al. 2014, Lin et al. 2018).

Studies adopting a socio-cultural perspective show dynamics of either converging or diverging preferences towards ES. Diverging preferences have been identified across different groups of stakeholders, for instance between local residents and local managers (Iniesta-Arandia et al. 2014, Riechers et al. 2017), or between stakeholders at regional and national scale (Garcia-Nieto et al. 2013, Ament et al. 2017). Assessments through social preferences suggest that non-material services are not a homogeneous group, thus nuancing their holistic nature assumed using a biophysical perspective: notably, recreation encompasses multiple forms which could compete which each other — for instance, areas of safari tourism are often not places where people can enjoy self-guided activities like hiking or fishing because of the danger posed by big species (Ament et al. 2017, Clements & Cumming 2017).

Conversely, the fact that some bundle features are similar across stakeholder groups reveal common perceptions and shared priorities: for instance, in Berlin, both experts and laypersons saw recreational values from nature as the most important benefit (Riechers et al. 2017), while all stakeholder groups shared similar views on critical ES in two watersheds in Southern Spain (Iniesta-Arandia et al. 2014). Furthermore, synergies assessed through elicited priorities concur with the previous observations that regulating and non-material ES often appear together (Hicks & Cinner 2014, Simpson et al. 2016). Interestingly, it has been reported that material ES can also be valued with other types of ES: for instance, the bundle of services perceived as vulnerable by local residents of a Spanish protected area comprised material and some non-material ES such as recreational hunting (Iniesta-Arandia et al. 2014); Hicks & Cinner (2014) have shown that fishers in Tanzania prioritise fishing, bequest (passing healthy ecosystems on to the next generation) and culture together (Hicks & Cinner 2014); Brown et al. (2015) have reported that forested areas in the Norwegian regions of Nordland and Sogn are perceived to provide multiple bundles supporting both material ES and recreation-related values (Brown et al. 2015).

A few studies have focused on identifying mismatches between the biophysical provision of ES and their societal demand. They reveal either unsatisfied demand in a specific location or spatial mismatches between the providing units and the benefitting areas of ES. For instance, Baro et al. (2017) found bundles showing higher ES demand than provision in the urban core of the Barcelona Metropolitan region, while Garcia-Nieto et al. (2013) highlighted a spatial mismatch for ES such as erosion control and nature tourism (provision at the local scale and demand at the regional–national scales). In contrast, similar bundles on the provision and demand sides have been detected in a forested area as well as in green suburbs of a metropolitan region (Garcia-Nieto et al. 2013, Baro et al. 2017).

1.2.4.3 Drivers of ES consistent associations

A large proportion of studies (70%) reviewed in Saidi & Spray (2018) go beyond the description of bundles and attempt to identify drivers, building on the assumption that consistency in ES associations emerges from common social-ecological drivers within a landscape. Three main types of drivers can be identified: (i) landscape and climate features, (ii) socio-economic conditions and (iii) institutional factors.

Landscape complexity in terms of composition and configuration are important factors in the formation of ES associations and therefore of bundles (Birkhofer et al. 2018). For instance, forest cover has been found to be a determinant of bundles of ES biophysical provision, and the urban-rural gradient seems to shape bundles identified in regions with a diverse landscape: for instance, a study in the region of Stockholm found that distance from the city centre strongly predicted the patterns found for most ES (Queiroz et al. 2015) and could therefore contribute to explaining the bundles identified in this region. In Denmark, there was a tendency for peri-urban landscapes to be important areas for non-material ES, which led to the 'multifunctional bundle' types to be situated around the larger cities (Turner et al. 2014). Climate aspects were also found to drive bundles of ES biophysical provision (Dai et al. 2017), with a study at the European scale even concluding that climate could be the primary driver of ES supply at the macro-scale (Mouchet et al. 2017). Furthermore, geomorphologic features of a landscape can act as drivers for some bundle types: for instance, shore areas were found to host tourism-dominated bundles in Germany and Denmark (Turner et al. 2014, Dittrich et al. 2017) — to be attributed notably to the scenic beauty of the sea (Turner et al. 2014). Areas with the best agricultural soils were also identified as locations with specialised bundles —for instance, a study in Quebec by Renard et al. (2015) showed that good soils were locations of bundles with a low diversity of services and dominated by crop production. Another study, in the Yangtze River Basin, found that slope and altitude gradients could explain—at least partly—the formation of bundles: material services were concentrated in flat areas (which also had dense cropland, wetland and the largest population density), while regulating services and high levels of biodiversity tended to be distributed in the mountain areas with high forest coverage (Kong et al. 2018). Landscape features also influence bundles of demand, since people prioritise or use services based on their interests but also on the landscape's ability to provide them (Hamann et al. 2015, Baylan & Karadeniz 2018).

Socio-economic drivers were identified in bundle studies adopting a biophysical perspective as well as in those adopting a socio-cultural perspective. From the biophysical side, acknowledging the social component of ES provision improved the ability to predict or model distributions of multiple ES across space and time (Raudsepp-Hearne et al. 2010); furthermore, one study found that socio-economic drivers had a greater contribution than natural endowment in explaining the variance in a set of 12 ES (Yang et al. 2015). From the socio-cultural perspective, factors such as income, education, occupation or authority were found to shape bundles of social preferences (Martin-Lopez et al. 2012, Plieninger et al. 2013, Hicks & Cinner 2014, Iniesta-Arandia et al. 2014, Riechers et al. 2017) or services consumption (Hamann et al. 2015). Changes in business models for land management also influence bundles: for instance, in an agricultural region in Quebec, the trend towards intensification of pork production since the 1970s has led to the spatial expansion of the bundle specialised in farm animal production (Renard et al. 2015). Another example can be found in South Africa where the National Parks' management decisions, motivated by income, contribute to shaping bundles of demand for non-material ES (Ament et al. 2017, Clements & Cumming 2017).

In addition to land use and socioeconomic factors, some studies have found that policy, in particular conservation and agricultural policy, may explain the features of some bundles. It appears that the presence of protected areas is associated with bundles containing regulating services, while bundles containing mainly material services are located outside of protected areas (or are more recognised by stakeholders who do not visit protected areas) (Martin-Lopez et al. 2012, Depellegrin et al. 2016, Baro et al. 2017). Historical changes in the bundle of services supplied by municipalities in Quebec revealed the potential role of agricultural policy in the structure of bundles (Renard et al. 2015): the operationalisation of a grain self-sufficiency policy, supported by subsidies and advances in technology, encouraged the production of cash crops at the expense of the dairy industry and hayfields that had been dominant since the 1850s in the region studied by Renard et al. (2015). In one paper, institutional factors other than policy have been identified as playing a role in the occurrence of bundles: Hicks & Cinner (2014) demonstrated that the bundles of ES prioritised in terms of contribution to well-being can be understood by the access mechanisms people have available to them, such as authority or social relations.

1.2.4.4 Limitations to the interpretation of bundles

To begin with, bundles will evidently differ depending on the ES actually included in the analysis. As a result, key associations could be missed or misinterpreted if ES relevant to the study area are omitted. Furthermore, the challenge of choosing or developing quantification methods for the selected services, although common to all ES assessments, is accentuated in the case of bundles: the structure of the resulting ES dataset, in addition to a study's objectives, will drive the selection of methods to identify bundles. In this context, a recurring concern in bundle research is the influence of spatial extent and resolution on the structure of bundles. Research has shown that bundles can be considered somewhat robust to changes in scale of observation, but that large changes may result in the reconfiguration of bundles if heterogeneously-distributed ES are involved: spatial units at larger scale would be found to provide these services at some level, while units at a higher resolution may not provide them (Raudsepp-Hearne & Peterson 2016). Furthermore, some have argued that study areas of different size but located in the same ecoregion would show similar bundles, while changing the extent of a study area to include part of a different landscape would lead to a reconfiguration of the detected bundles (Marsboom et al. 2018). The key lesson perhaps is that analyses of bundles of ES require careful consideration of which observation scale is appropriate and which area extents are the most relevant.

There are also important limitations to drivers identified in published bundle studies. Although some studies have done so qualitatively, only quantitative methods such as redundancy analyses or regression models have the ability to robustly identify drivers for bundles(Mouchet et al. 2014, Spake et al. 2017). A major issue for understanding causal drivers of supply bundles is that most ES are modelled rather than measured; therefore, an element of circularity exists in a lot of studies, resulting from assessing the relationship between socio-ecological variables and ES derived from these same variables (Spake et al. 2017). Analysis is further made difficult by the interconnection between identified drivers, with for instance land use being itself driven by agricultural policies or social relations in a landscape.

1.2.5 Bundles and decision-making

Although no published evidence reports the use of bundle approaches in decision-making, the literature offers reflections on the promising role of bundles in this respect (Saidi & Spray 2018). They focus on decisions related to land-use planning and management and suggest that bundles have the potential to be integrated at different stages of the decision-making process — from problem definition to implementation (Table 1.3).

Table 1.3: Hypotheses formulated in the literature regarding the potential contribution of ecosystem services bundles to decision-making. Reproduced from Saidi & Spray (2018), full references therein.

Phase of the decision-making process	**Potential role of bundles**
Scoping and defining the problem	Identifying socio-ecological challenges faced in different areas from the different bundle profiles that exist across a landscape
	Identifying the scale of responsibilities for the management of services, depending on the scale at which the interactions are identified
Design of policy / planning options	Designing initiatives that target multiple ecosystem services simultaneously
	Promoting the integration of ecosystem services in policies and actions targeting other objectives, such as conservation
Assessing options	Showing the co-benefits or the negative impacts of land use policy options (habitat restoration, sparing strategies, cropping systems, etc.) on the provision of multiple ecosystem services
	Improving the deliberation process knowing the bundles of preferences across the stakeholder groups potentially affected by the policy or action
	Comparing options with regards to how they change the contribution of ecosystem services to well-being
Implementation and revision	Monitoring changes in bundles through time and adapting action plans as needed.

However, current literature falls short of conducting in-depth analyses on how bundle knowledge could effectively be used in decision-making related to land-use planning and management. Achieving effective use - i.e. producing bundle knowledge which is salient, credible and legitimate- cannot be considered as straightforward, as explained in section 1.2.2. Two main reasons can be identified. First, bundle knowledge attempts to offer an integrated perspective of the complex issue of interrelationships among many

ES, which involves uncertainties, diverse values and various areas of decision-making. As a result, achieving salience, credibility and legitimacy requires to navigate the 'complexity-clarity' and 'speed-quality' trade-offs (see section 1.2.2). Second, bundle knowledge can be considered policy-relevant based on the literature, but it is not currently policy-demanded ('push-pull' trade-off). As a result, contextual conditions regarding the 'mainstreaming' of ES in decision-making – i.e. the extent to which the ES concept is integrated therein – is likely to play an important role in the types of uses that can be effectively achieved (Sarkki et al. 2014).

There is therefore a need to better understand how to produce credible, salient, and legitimate bundle knowledge; recognising that these attributes would depend on the conceptual, strategic, or instrumental uses that are sought - or are indeed possible - considering the level of integration of the ES concept in decision-making. Based on reflexions of Sarkki et al. (2014), I argue / hypothesise that bundles can effectively be used conceptually, strategically, and / or instrumentally, meaning: conceptual, strategic, and instrumental uses can be identified, for which bundle knowledge can be salient as well as credible and legitimate, depending on how that knowledge was produced and the extent to which ES are mainstreamed.

1.3 Research question and aims

The thesis addresses the following general research question:

How could knowledge derived from ES bundle assessments be effectively used in decision-making related to land-use planning and management?

More specifically:

What conceptual, strategic, and instrumental uses of ES bundle knowledge would ease trade-offs between its salience, credibility and legitimacy, depending on the current mainstreaming of the ES concept?

The research question is addressed with a case study approach in the urban environment: the rationale for the choice of landscape and the specific case study is described in the next section (section 1.4). To address the research question, the thesis is articulated around five aims, which are further detailed in section 1.5:

- Developing and implementing a bundle approach by following principles of salience, credibility and legitimacy;
- Identifying and analysing the ES interrelationships that can be evidenced from the implementation of the developed bundle approach;
- Identifying salience, credibility and legitimacy criteria for bundle knowledge, based on lessons-learnt from the case study;
- Describing and discussing the current integration of the ES concept in high-level urban decision-making;
- Discussing the potential instrumental, conceptual, and/or strategic uses of bundle results given their salience, credibility and legitimacy attributes, as well as the decision-making context around ES.

The scope of the thesis in terms of types of bundles, landscape, and decision-making, is detailed and explained in the next section.

1.4 Scope of the thesis

1.4.1 Types of bundles investigated

As described in section 1.2.4.1, bundles can be of different types: ES Bundles, Spatial Bundles or Perception Bundles. Although there is evidence that land-use planning and management has been supported by spatial ES assessments (Bai et al. 2018, Barral & Oscar 2012, Kopperoinen et al. 2014), the consideration of the socio-cultural perspective of ES, notably through the study of perceptions and preferences, have not permeated this type of decision-making to the same extent. In addition, sampling participants across a diversity of stakeholder groups, and eliciting their preferences, would involve timeframes that could be too long for the research questions to be realistically investigated in three years. Considering these two points, and while recognising the relevance of Perception Bundles to the research questions, this thesis focuses on the contributions of ES Bundles and Spatial Bundles.

Furthermore, bundles of ES have been investigated in different types of land uses at different scales, as described in section 1.2.4.2 This thesis focuses on the urban environment and explores the research questions in the City of Edinburgh: the rationale for the choice of landscape and the specific case study is described in the next sections.

1.4.2 Rationale for exploring the research questions in the urban environment

1.4.2.1 Contribution of urban nature to a good quality of life and knowledge gap on urban ES associations

More than half of the current global population lives in urban areas, a proportion expected to rise to 66% in 2030 (UN DESA 2015). Urban population growth, coupled with an increasingly complex system of interconnected institutions, infrastructure and information, makes cities ever more vulnerable to shocks and pressures (Elmqvist et al. 2019). At the same time, although they have always faced challenges such as resource shortages, natural hazards and conflicts, cities are exposed to increasingly pressing environmental issues and climate change related risks such as droughts, flooding and heat stress (De Bono et al. 2013, Elmqvist et al. 2019). In this context, the UN issued a call for safer, more inclusive, resilient and sustainable cities through the eleventh Sustainable Development Goal (SDG11) of the 2030 Agenda for Sustainable Development (United Nations 2015).

The natural environment within urban areas can play a pivotal role in the achievement of this goal by mitigating environmental burdens, contributing to climate change adaptation, and increasing public health and social cohesion (Baró et al. 2019). Most urban ES, such as temperature regulation or noise reduction, must be provisioned locally and cannot be imported – man-made substitutes, when they exist, are often carbon-intensive and expensive (Elmqvist et al. 2015, McPhearson et al. 2015). Therefore, protecting and enhancing urban ES is critical to ensuring urban sustainability and well-being, especially in a context where demand for these services is expected to increase (McPhearson et al. 2015, Kabisch et al. 2015).

Recent years have seen an increasing recognition of the importance of nature in providing multiple benefits in urban areas, beyond aesthetics and recreational values (Haase et al. 2014, Geneletti et al. 2020), especially in relation to the on-going Covid-19 pandemic. Based on growing scientific evidence – overwhelmingly from the developed world – 'greening the city' has become an imperative for urban planning, with the emergence and mainstreaming of planning strategies to improve urban greenspace systems, under the names "green infrastructure" or "nature-based solutions" (Hansen et al. 2017, Tzoulas et al. 2007) . Compared to engineered solutions, which are by definition tailored to specific problems, nature-based solutions often provide multiple ES. However, these benefits are harder to estimate and are poorly studied (Keeler et al. 2019, Hansen et al. 2019). In particular, an anecdotal number of bundle studies have been conducted in urban areas (Saidi & Spray 2018).

1.4.2.2 Restricting the scope to strategic decision-making in cities in the developed world

a. ES and decision-making at city-level

It has been argued that the presence of ES-related approaches in urban planning precedes the emergence of ES as a concept (Cortinovis & Geneletti 2018, Lam &

Conway 2018). Namely, strategies and plans related to greenspaces have traditionally included some non-material services, especially recreation, without planners necessarily framing them as ES (Cortinovis & Geneletti 2018, Kabisch 2015). More generally, in current urban plans, the ES concept and ES themselves are often implicitly referred to, either being described with alternative terminologies - for instance "values" or "benefits" - or in discourses about human-nature relations or the dependence of human well-being on nature (Wilkinson et al. 2013, Hansen et al. 2015, Nordin et al. 2017). In parallel, urban planning documents and practices have also been including the ES concept and individual services in an explicit manner, driven by local and regional political priorities, national policies and the scientific support available to translate scientific evidence into practice (Cortinovis & Geneletti 2018, Hansen et al. 2015).

The integration of the ES concept in planning has been occurring at three main levels (Hansen et al. 2015, Kabisch 2015, Frantzeskaki & Tilie 2014): in framing vision, strategy and long-term goals; in developing short-to-medium term programmes and action plans; and in implementing plans and programmes. The inclusion of ES-related information across these three levels is not necessarily coherent: existing studies report both the loss of the ES concept when going from vision to implementation (Nordin et al. 2017, Frantzeskaki & Tilie 2014) and the use of ES as a supporting tool in plans and their implementation in existing approaches which are not necessarily ES-based (Cortinovis & Geneletti 2018, Hansen et al. 2015, 2019). The use of the ES-concept at the vision and strategy level is most often observed in cities located in countries or regions where the ES-concept has permeated policy early, for instance New York, Seattle, Stockholm or Malmö (Hansen et al. 2015, Nordin et al. 2017). Although the breadth of ES considered tends to be broad (Hansen et al. 2015), an emphasis on recreation and biodiversity has been noticed, reflecting political priorities, especially regarding recreation (Cortinovis & Geneletti 2018, Lam & Conway 2018), and the influence of higher-level policies, such as the EU Biodiversity strategy (Hansen et al. 2015). When the ES concept is integrated at the level of action plans and their implementation, it involves the use of ES-related tools to design greenspaces for environmental purposes, such as better water flow regulation (Cortinovis & Geneletti 2018, Hansen et al. 2015).

Current integration of the ES concept at city-level decision-making, as described above, remains limited. Indeed, it is hindered by a lack of awareness of the importance of considering ES (Cortinovis & Geneletti 2018, Rall et al. 2015), as well as a lack of guidance on both conceptual and technical aspects (Kaczorowska et al. 2016, Hansen et al. 2015, Kabisch 2015). At implementation-level, the lack of availability of high-resolution, site-specific information hinders the uptake of ES tools for the design and planning of greenspaces (Cortinovis & Geneletti 2018, Hansen et al. 2019); so does the limited integration of the demand side of urban ES in currently available assessments (Cortinovis & Geneletti 2018, Kaczorowska et al. 2016). At strategy-level, the uptake of the ES concept would be eased by guidance on how to turn the concept into specific objectives and targets (Nordin et al. 2017), but very much depends on political decisions and the planner's expertise. At all levels, active involvement from research and the wider scientific community has been identified as a key factor in translating the ES concept into planning (Kaczorowska et al. 2016, Lam & Conway 2018).

b. Restricting the scope

Cities in the developed and developing worlds have different challenges in term of land-use planning and management, which prompted a restriction of the scope of investigation. Because the knowledge base on ES and ES-related decision-making is larger in developed areas, as mentioned in the section above, the scope of the thesis is restricted to developed cities. Indeed, it was important to limit problems with data availability and access issues to the extent possible, in order to increase the likelihood of exploring all aspects of the research question within the timeframe of the study.

The relevance of the ES concept to all levels of urban decision-making, from vision to strategy to implementation, also called for a focus in the scope of the thesis' research questions. I choose in this study to focus on the strategic aspect of city-level decision-making, a denomination under which I include the framing of long-term visions as well as medium-term strategies and action plans. This focus is motivated by the fact that strategic decision-making is an established practice in most developed countries, while implementation practices tend to be context specific (Wilkinson et al. 2013). As a result, focusing on strategic decision-making enables a better contribution of the thesis to the wider body of knowledge on the potential use of bundles.

1.4.3 Exploring the research questions in the City of Edinburgh

1.4.3.1 Rationale for a case study design

Each of the aims defined in section 1.3 correspond to a different unit of analysis, requiring different methods and relying on different sources of evidence. Answering the overall research question will therefore involve the integration of different types of findings, such as outcomes of statistical analyses or qualitative results derived from interviews. Exploring and integrating different units of analysis across disciplines with a case study design, an approach called "embedded case study design", has been found to provide a pragmatic research tool for interdisciplinary studies (Yin 2018): it is increasingly used in environmental research for integrating different sources of evidence and gaining more insight into complex issues (Scholz & Tietje 2002).

While recognising that a multiple case design would provide more robustness to the analysis (Yin 2018), the thesis relies on a single case study to ensure these tasks are addressed in enough depth in the timeframe of the PhD project. A crucial point in the research design is then to understand the extent to which the conclusions generated for this single case study could be extended to other contexts. One way to enable the discussion of the study's external validity is to investigate the research questions in a context which is *a priori* favourable to the use of bundle results at strategic level. This meant selecting a city with a strong indication of commitment from authorities to the stewardship of ecosystems, and with a good availability of the diverse sources of data necessary to conduct the study.

1.4.3.2 Selection of Edinburgh as a case city

The City of Edinburgh satisfies the two criteria introduced above. In addition to nationwide publicly available land cover data at high resolution, city-specific data is available through a dedicated portal (see Chapter 3, section 3.4 for a detailed description of data sources). Based on existing methodologies to assess biophysical urban ES provision, there was a high degree of confidence that a wide range of ES values could be derived from the type of data identified at this preliminary stage. The availability of both data and valuation methodology meant that the credibility and legitimacy of a bundle approach was likely to depend on the bundling itself rather than on the preliminary quantification process.

Furthermore, Edinburgh is a city where there is a visible commitment to greenspaces. In addition to a web-based search finding a plethora of projects and programmes related to green paces and their benefits, an informal discussion with the manager of the City's Parks & Greenspace service confirmed the dynamism and responsiveness of the city in this regard. The manager also showed an interest in the study at a preliminary stage, which was an additional argument for selecting Edinburgh as a case study. His interest meant an increase chance of getting feedback on the salience, credibility and legitimacy of the approach, as well as explore how bundle results could be of use to his team. Furthermore, he was a key informant for the exploration of the decision-making context around nature in Edinburgh. He also offered his help in identifying other key people across the city's departments (see Chapter 4, section 4.4).

The following table reports the nature and timeline of interaction with the manager of the Greenspace service, Mr David Jamieson.

Table 1.4: Nature and timeline of interactions with the manager of the Greenspace service of the City of Edinburgh Council

When	Nature of interaction	Purpose
June 2018	Informal face-to-face discussion at Council premises	Starting the collaboration relationship (Introductions by Pr Chris Spray) Sharing the aims of the PhD project Getting familiar with projects in Edinburgh
December 2018	Face-to-face meeting at Council premises	Co-selection of relevant ES (section 3.3) Getting feedback on, and inputs into, the relevant geographical scales and extent (section 3.2) Getting feedback on, and inputs into, sources of data (section 3.4) Getting updates on current projects in Edinburgh
May 2019	Face-to-face meeting at Council premises. *Also present: Ian Mackenzie (Scottish Wildlife Trust)*	Feedback on a methodological note shared prior to the meeting: quantification models and preliminary ES maps (section 3.4.2)

continued . . .

...continued

When	Nature of interaction	Purpose
September 2019	Email communication	Sharing of contact details of a senior staff across relevant remits within the Council, for interview (section 4.4.2)
November 2019	Face-to-face meeting at Council premises. *Also present: Donya Davidson, project officer, Ecological Coherence Plan*	Discussing preliminary bundle results and getting first insights into how bundles could be useful to the Greenspace service's needs (section 6.5)
		Getting feedback and additional suggestions on a preliminary list of strategy documents (section 4.3.3)
August 2020	Email communication	Validation of the mapping of city-level strategical frameworks and action plans (section 5.2)
September 2020	Virtual meeting (video call)	Discussing a preliminary list of uses established based on results from the bundle assessment, the current integration of the ES concept, and consideration of salience, credibility and legitimacy (section 6.5)

1.5 Analytical structure of the thesis

The thesis is divided into six chapters (Figure 1.2).

This chapter, **Chapter 1**, provides a background on the ES concept and the use of ES knowledge in decision-making, before introducing bundle approaches as a promising way to contribute to decision-making. It then states the study's research questions and defines the scope of the thesis: studying the contribution of ES Bundles and Spatial Bundles to strategic decision-making in an urban environment. The research design devised to address the research questions, namely the choice to conduct a single embedded case study in the City of Edinburgh, is then presented.

The thesis is then organised in three parts. The first part addresses the first aim of the thesis by focusing on the identification and analysis of ES Bundles and Spatial Bundles. It consists of two chapters:

- **Chapter 2** is a methodology chapter. It presents the development of a bundle approach suited to ES with heterogeneous spatial distributions. The bundle approach is informed by a systematic review of bundle methodologies and consists of a set of methods to i) quantify the individual ES, ii) identify bundles and iii) identify drivers of these bundles.

- **Chapter 3** is a result chapter. It presents the implementation of the methodology developed in Chapter 2 to identify and analyse bundles of ES in Edinburgh. In particular, the breadth of bundled ES and the scale of assessment is determined according to the study's scope and through communications with the city's Parks & Greenspace service.

The second part addresses the fourth aim of the thesis by focusing on the study of the decision-making context around ES. It consists of two chapters:

- **Chapter 4** provides a methodology to explore the decision-making context around the contribution of nature to people in urban areas. It shows how this context can be understood as the extent to which the ES concept has been integrated in decision-making. After defining the term "integration", Chapter 4 presents a mixed-method approach consisting of document analysis and key informants' interviews.

- **Chapter 5** is a result chapter. It is dedicated to the investigation of the decision-making context in Edinburgh following the methodology developed in Chapter 4.

The third and last part of the thesis contains the discussion chapter and the conclusion:

- **Chapter 6** addresses the second, third and fifth aims of the thesis by discussing results from Chapters 3 and 5:
  - It identifies and analyses ES interrelationships evidenced by bundle results from Chapter 3;
  - It identifies salience, credibility and legitimacy criteria for bundle knowledge, as well as trade-offs among them, based on lessons-learnt from Chapter 2, 3 and 5;
  - It answers the study's research question by discussing the potential instrumental, conceptual, and/or strategic use of bundle results given their salience, credibility and legitimacy attributes, as well as the decision-making context around ES.

  Limitations are also presented, and avenues for future research are outlined.
- **The conclusion** closes the thesis by summarising the conclusions of the study.

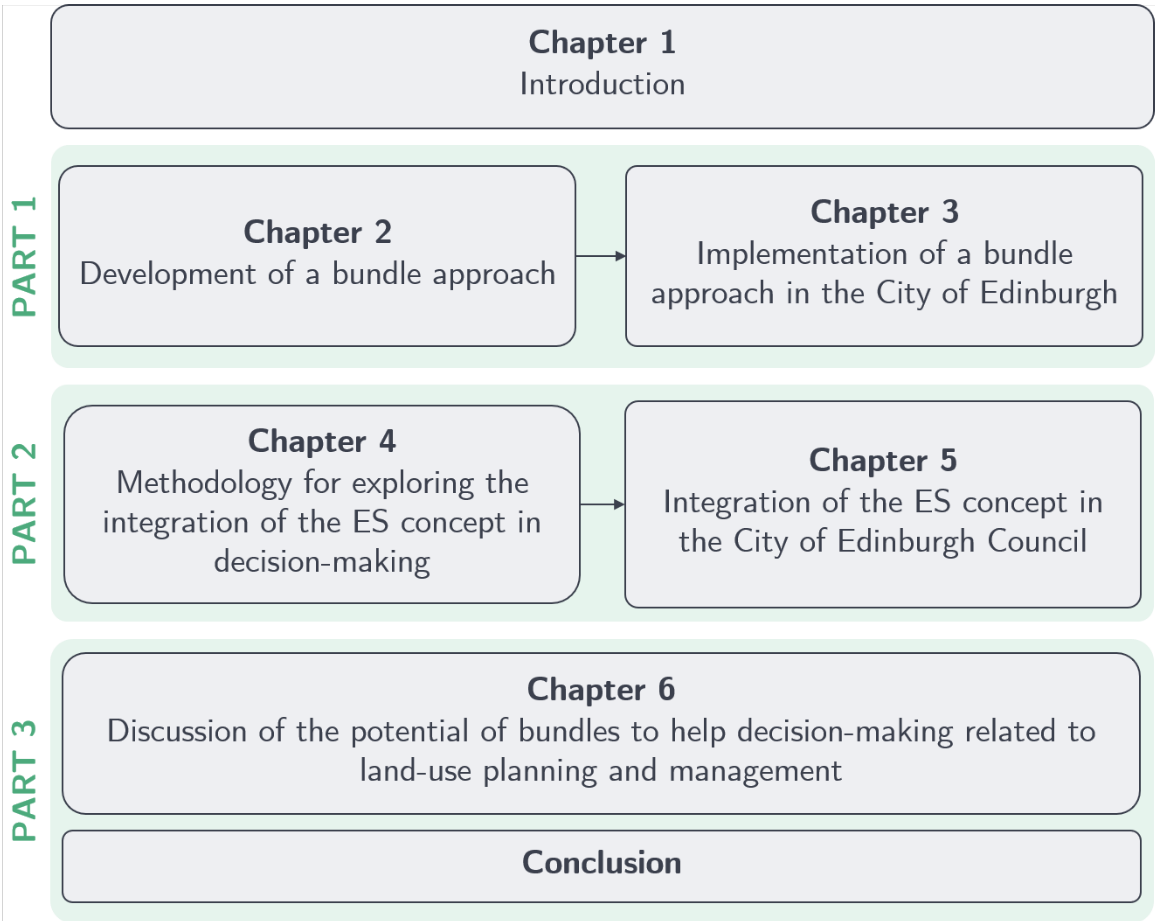


Figure 1.2: Structure of the thesis

Chapter 2

Development of a bundle approach

2.1 Introduction

This Chapter presents an approach to identify and analyse bundles of provision of ES with heterogeneous distributions. The approach consists in a set of methods which were developed based on a review of existing methodologies (section 2.2). The expected structure of the dataset obtained from the quantification of individual services prior to bundling (section 2.3.2) informs the choice of methods to identify ES Bundles (section 2.4) and Spatial Bundles (section 2.5). Methods for analysing bundles, in particular identifying drivers of their formation, are laid out in section 2.6.

2.2 Review of bundle approaches and implications for this study

A systematic review was conducted as part of this study and published in Saidi & Spray (2018). The findings regarding methods to identify and analyse bundles are summarised in this section, while the methodology for the systematic review is reproduced in Appendix A.

2.2.1 Bundle identification

A bundling approach consists in detecting structure in a multivariate dataset of ES values, followed by an analysis of this structure to identify implications for decision-making. The term "dataset" refers here to a matrix reporting ES values for each spatial unit under consideration (Figure 2.1). In this matrix, ES are the variables (columns) and spatial units the observations (rows).

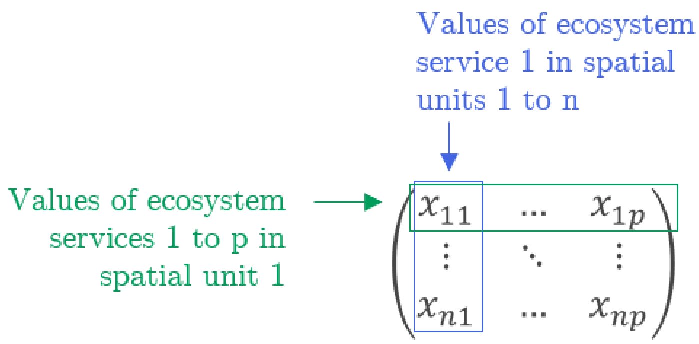


Figure 2.1: Structure of the dataset

As explained in section 1.3, the two types of approaches investigated in this study are 'ES bundles' and 'Spatial Bundles' (this terminology is specific to the study).

ES bundles are defined in this study as groups of ES consistently associated together. Identifying these groups refers to the broader statistical problem of detecting clusters of *variables* within a multivariate dataset. The most common strategy, in general and in bundle studies, is to project the data into a small number of dimensions preserving their multivariate structure as fully as possible (ordination in reduced space) (Everitt 2011, Saidi & Spray 2018). Groups of variables – or ES bundles in the context of this study – are then identified graphically or tabularly in the reduced dimensional space. In bundle studies reviewed in Saidi & Spray (2018), ES datasets are mainly projected using Principal Component Analysis (PCA) (Bai et al. 2011, Turner et al. 2014, Depellegrin et al. 2016). Other techniques used are factor analysis (Qiu & Turner 2013), Multiple Correspondence Analysis (MCA) (Garcia-Nieto et al. 2013) and multidimensional scaling (MDS) (Riechers et al. 2017).

'Spatial bundles' are defined in this study as groups of spatial units identified based on the similarity of their ES values. Identifying these groups refers to the broader statistical problem of detecting clusters of *observations* within a multivariate dataset. In general and in bundle literature, this problem is commonly addressed using hierarchical-based or centre-based clustering analyses: close to 80% of spatial studies reviewed in Saidi & Spray (2018) use such methods, which look to minimise the dissimilarity among spatial units belonging to the same group:

- Hierarchical clustering produces a nested set of partitions by merging (or splitting) groups in a step-by-step sequence. The decision at each step is based on the similarity between the elements or groups to merge (or split). One then has to decide at which level of merging (or splitting) to divide the nested partitions into groups of observations – here bundles of spatial units (e.g. Dai et al. (2017), Roussel et al. (2017)). An illustrative example is provided in Figure 2.2.

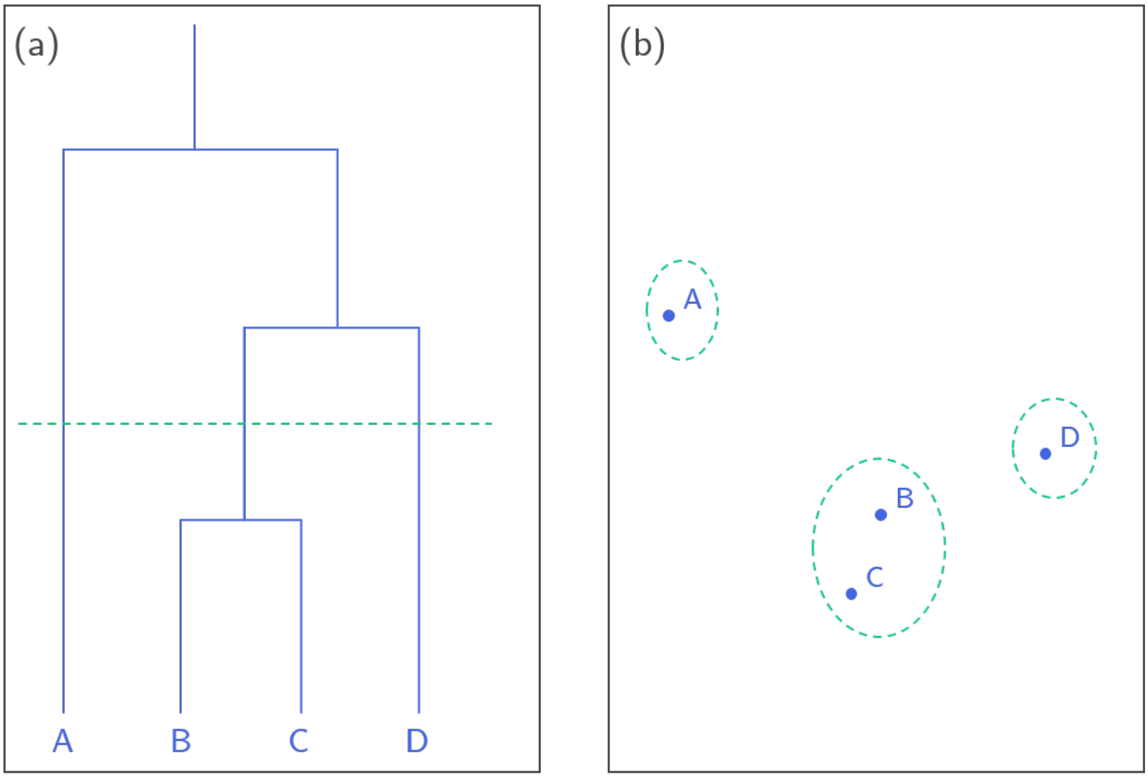


Figure 2.2: Example of four objects clustered in three distinct groups after splitting a nested partition obtained from hierarchical clustering. (a) Dendrogram of four objects – A, B, C, D – showing the results of a hierarchical analysis. The green dotted line indicates the cut at three branches as an example. (b) Diagram showing the three groups produced by the cut.

- Centre-based clustering finds all clusters at once by minimising the difference between observations and pre-defined cluster centres. Given a number k, many combinations of k centres and partitions are tested by the clustering algorithm in order to find a minimum to the function representing the difference measure. Among these methods, k-means is the most widely used in bundle literature (e.g. Raudsepp-Hearne et al. (2010), Queiroz et al. (2015), Lin et al. (2018)).

Other techniques to identify Spatial Bundles are self-organising maps (Crouzat et al. 2015, Dittrich et al. 2017), multivariate regression trees (Lamy et al. 2016) and PCA (Ryschawy et al. 2017).

The strategies governing the application of ordination or clustering methods for bundling mainly depend on the structure of the dataset (Saidi & Spray 2018). Three main trends can be identified across the literature:

- Studies identifying Spatial Bundles from a dataset with a high number of services (higher than 15) reduce its dimension first, for instance with a PCA, then use the projections on the two main factors as input for clustering analyses (Turner et al. 2014, Ryschawy et al. 2017). When hierarchical clustering is used, this initial projection may help address the memory consumption problems associated with this method. More generally, for some datasets, partitioning methods do not usually perform as well in high dimensions as they do in 2 or 3 dimensions - therefore, data projection may help improve the bundling performance.

- The bundling methods introduced above do not assume a specific distribution of data (e.g. normal distribution). Therefore, data transformation prior to bundling is not required. However, a few studies limited the skewed variances of their ES, which could respond heterogeneously to clustering or ordinal analyses, using log or square root operations (Turner et al. 2014, Crouzat et al. 2015, Renard et al. 2015).

- Studies working with ordinal variables, e.g. from expert-based scoring, rely on hierarchical clustering or a dimension reduction technique (mainly PCA) (Plieninger et al. 2013, Depellegrin et al. 2016, Roussel et al. 2017). The lack of use of k-means, which is otherwise popular across bundle studies, is due to the domain of validity of this technique, which covers interval data but not discrete data.

Nevertheless, very few studies justify their choice of ordination or clustering method. In particular, it is not clear how authors verify assumptions underlying the use of some methods, or how the structure of their data influences the interpretation of the identified bundles. Furthermore, *a posteriori* assessments of how well ES or spatial units have been bundled - i.e. the extent to which bundle identification is meaningful - is the exception rather than the norm.

2.2.2 Bundle analysis

The study of synergies and trade-offs often go beyond the identification of bundles. Additional analyses such as the detection of associations between pairs of ES, for instance by performing Pearson's or Spearman's correlation tests, are useful to understand the strength of trade-offs or synergies within a bundle or between bundles (Birkhofer et al. 2018, Depellegrin et al. 2016, Kong et al. 2018, Yao et al. 2016). Another practice is to analyse the richness or diversity of ES with techniques such as overlap analysis or evaluation of the Simpson's diversity index (Lin et al. 2018, Marsboom et al. 2018, Renard et al. 2015).

In addition to these supporting analyses, identifying drivers for bundle formation has been a major feature in bundle-based studies of trade-offs and synergies (Spake et al. 2017). It has been done both qualitatively and quantitatively across the literature. Qualitative interpretation involves understanding where in a landscape trade-offs and synergies are the strongest, generally using interpretation of PCA axes and scores (Balzan et al. 2018, Hanspach et al. 2014, Queiroz et al. 2015). Nevertheless, only quantitative methods such as canonical analyses or regression models have the ability to robustly identify drivers for bundles. Whereas qualitative methods are exploratory, quantitative methods rely on the identification of candidate social-ecological variables that are important in explaining or predicting different bundles of ES at a specific scale (Rositano et al. 2018, Schulze et al. 2016, Lamy et al. 2016). This initial selection is based either on relationships demonstrated in the primary literature or on expert knowledge.

2.2.3 Implications for the study

It appears from the review that a bundle approach can be divided into three basic phases: i) Quantifying each individual service across all spatial units in order to build the initial dataset; ii) Identifying and describing bundles and iii) Analysing bundles. The study's methodology for these phases, as described in the following sections, were heavily informed by the review's conclusions:

1. Quantifying the individual ES (section 2.3):

   The quantification strategy was designed based on salience, credibility and legitimacy criteria that are relevant at this stage (section 2.3.1). Because the outcome of this strategy greatly influences the choice of bundling methods, the expected structure of the resulting dataset is discussed in section 2.3.2 and has played an important role in shaping the methodology for the following phases.

2. Identifying and describing bundles (sections 2.4 and 2.5):

   - The review has shown that both the approaches of ES Bundles and Spatial Bundles help in identifying and analysing synergies and trade-offs (see Chapter 1). Therefore, both approaches were included in the study (sections 2.4 and 2.5 respectively).

   - One of the main lessons learnt from the review is the absence of a one-size-fits-all methodology for identifying and analysing bundles. Based on the recommendation from the review, the expected structure of the initial dataset has been the main driver for the choice of statistical methods. Previous bundling practices have been used to identify suitable methods; however, their shortcomings in terms of verifying assumptions, robustness or testing grouping quality have been covered by reviewing additional methods from a selection of relevant statistics books (Borcard et al. 2011, Legendre & Legendre 2012, Husson et al. 2017, Everitt 2011), in an effort to ensure the credibility of the proposed approach. All methods for bundle identification which are part of this study's approach are introduced and discussed in sections 2.4 and 2.5 along with the rationale for their selection.

3. Analysing bundles (section 2.6):

   - The qualitative interpretation of bundles regarding trade-offs and synergies is supported by an additional computation of pair-wise correlations in order to discuss the strength of these interrelationships.

   - In accordance with recommendations from Mouchet et al. (2014) and Spake et al. (2017), drivers are identified by studying the influence of pre-selected socio-ecological variables on bundle results. Such a quantitative approach reinforces the credibility of the approach (see section 6.4.2.2).

The following sections lay out in detail the methodology developed for each of these three main phases.

2.3 Quantification of the individual ecosystem services

2.3.1 Methodology

The objective of this section is to define a general methodology for the assessment of individual services before bundling. The general methodology sets criteria and steps that ad-hoc methodologies developed for the purpose of a specific context should follow. The development of a general methodology recognises that specific methodological aspects such as data collection or the use of specific methods should be left at the discretion of each bundle study to ensure its salience, credibility and legitimacy.

One of the recent reviews on the quantification of urban ES (Haase et al. 2014) shows that various approaches have been used to spatially assess their provision, among which are: empirical methods or models, biophysical evaluation models, statistical inferences and look-up tables. The selection of suitable methodology for this study was done considering aspects of salience, credibility and legitimacy that can be controlled at this stage:

- Salience- Aspect S1: Collection of input data should not be resource-intensive, to fit with decision-makers' limited time and manpower. It should also provide for the use of readily-available data sources.
- Credibility:
  - Aspect C1: Input data should have a high spatial resolution, to adequately represent urban greenspaces.
  - Aspect C2: Output data should be continuous and not ordinal, as much as current knowledge allows, in order to increase confidence in and robustness of the identification and analysis of bundles. This means that valuing ES indicators as scores should be avoided where existing literature allows to infer a physical, continuous value from spatial data. This may not be possible for all ES.
  - Aspect C3: Where possible, uncertainties should be quantified.
- Legitimacy- Aspect L1: to be legitimate, the choice of a methodology should be unbiased and rely on proven methods which comply with salience and credibility criteria.

The methodology was developed using guidance developed by the OpenNESS project (OPErationalisation of Natural capital and Ecosystem Services). Funded by the European Union under its 7th Framework Programme, it aimed to translate the concepts of Natural Capital and ES into operational frameworks. One of its outputs is a technical document providing comprehensive guidance for selecting fit-for-purpose methods to assess ES (Barton et al. 2017). The recommendations are based on the review of application of ES appraisal methods applied in 27 case studies covering different land, water and urban decision-making contexts. Notably, the report features decision trees providing a step-wise framework for identifying the best method(s) suitable to a specific purpose. The path through the branches of the " biophysical methods" decision tree is highlighted in Figure 2.3 and identifies the Advanced Matrix Mapping (AMM) approach as suitable for this study.

A proposed definition for the AMM approach, from the description provided in (Barton et al. 2017), would be:

"Advanced matrix mapping approaches build on 'simple matrix' approaches. A simple matrix approach links land cover categories to ES indicators, which can be derived from scientific data or can be scores based on local or expert knowledge. Their aim is to generate maps of ES. A so-called 'advanced' matrix approach goes further by incorporating multiple sources of spatial datasets, such as modelled or monitoring data."

Therefore, an AMM involves i) modelling the relationship between spatial data and ES indicators and ii) implementing the developed models in a Geographic Information System (GIS). This approach can be considered legitimate for the study. To comply with salience and credibility criteria, an ad-hoc AMM methodology should include the following steps:

1. Identifying spatial data complying with criteria S1 and C1.
2. Developing models of the relationships between the datasets and the selected ES, the outputs of which should comply with criteria C2 and C3. These models are based on results from existing empirical studies (criterion L1).
3. Implementing the models in a GIS software.

This methodology is similar to the one developed for a study quantifying multiple ES

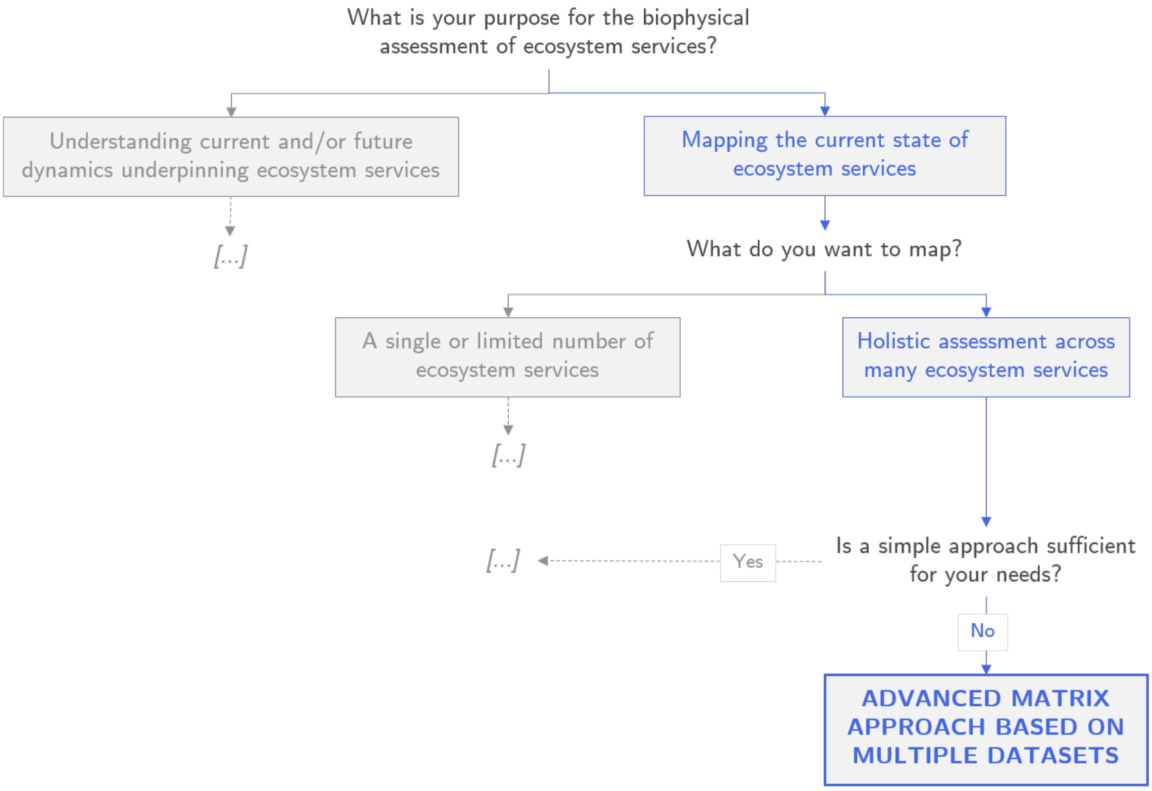


Figure 2.3: Selection of a mapping approach using the OpenNESS decision tree. The blue arrows and boxes show the pathway for the study. Tree branches which are not applicable to the study are not reproduced (dotted arrows and triple dots).

in Rotterdam (Derkzen et al. 2015), as well as the one used to develop the assessment tool EcoSERV-GIS (Winn et al. 2015).

2.3.2 Expected structure of the resulting dataset

The dataset will feature continuous values of services measured in different units, which means that the services will not be directly comparable. This specificity will be important when dealing with statistical methods sensitive to the similarity in scale and variance of the studied variables.

Spatial distributions of urban ES will differ from one another, however we can expect to find the following characteristics:

- Most services are expected to be positively skewed, i.e. to have the bulk of their values lower than their mean, with high values for only a few spatial units - the units which feature the right combination of environmental parameters (e.g. high land cover of trees and water features) to give a high provision of the services.

- For some services, this skewness is expected to be extreme; these are services which are very localised or only provided in areas where non-sealed surfaces are above a certain threshold. In many spatial units, the value of these services will be zero, while for a few of them, high values will be observed.
- Conversely, some services may be negatively skewed, i.e. have high values for most spatial units and low values for only a few of them.

Therefore, the distribution of most - if not all - services is likely to strongly diverge from normality, which has implications for the implementation of any statistical method based on variance. Indeed, the variances of these services will not be representative of their variability; rather, they will be driven by the extreme values in the distribution. This brief description of the initial dataset highlights the need to consider non-parametric statistical methods, or at least the need to consider data transformation and scaling if the more common, variance-based methods are to be used.

2.4 Identification of ES Bundles

2.4.1 Brief description of PCA and its properties

The aim is to identify groups of services consistently associated together. The most commonly used tool to summarise the main relationships between variables in a visual manner is PCA (Husson et al. 2017), which has been routinely used in bundle studies (see for instance Maes et al. (2012) or Balzan et al. (2018)). PCA transforms the studied variables into new variables, called principal components, which are uncorrelated with each other and which account for decreasing proportions of the total variance of the original variables (Everitt 2011). As a result, the first few principal components can often contain most of the variability of the dataset and allow a representation, in reduced space, of the variables (e.g. two dimensions if only the first two components are retained).

PCA works on an association matrix, i.e. a matrix containing: the variances and covariances of the variables when they are dimensionally homogeneous, or the correlations computed from dimensionally heterogeneous variables (Borcard et al. 2018). PCA detects linear relationships and preserves Euclidean distances.

2.4.2 The need for transformation-based PCA

2.4.2.1 Origins of transformation-based PCA: the double-zero problem in community ecology

Interpretation of datasets with variables having a large proportion of zeroes generates the so-called 'double-zero problem', commonly described when studying species abundance data: because species tend to be absent from ecological sites far from their optimal living conditions, abundance data from situations involving strong environmental gradients typically contain many zero-values. While the presence of a species at a given site generally implies that this site provides a set of minimal conditions allowing the species to survive, the absence of a species from a site may be due to a variety of causes. Therefore, two sites having a value of zero for the same species should not systematically be considered as similar: this is the 'double-zero' problem. As a result, association measures treating zeroes as any other value in order to infer associations between species would lead to potentially misleading interpretations. Covariances or correlation coefficients are such measures, which additionally fails to recognise associations between variables which are not in a linear relationship. Therefore, conducting a PCA directly on species abundance data is not recommended.

Transformation-based PCA (tb-PCA) has been proposed by Legendre & Gallagher (2001) as a way to address the issue. This method consists in two steps:

1. Transforming the rows of the dataset into profiles or modified profiles of relative species abundance;
2. Conducting a PCA on the transformed dataset.

Such a PCA allows for the distances between sites to be more accurately represented than with a simple PCA, by reducing the influence of zeroes and very low values in the variability of the dataset. This leads to the identification of more meaningful principal components than a simple PCA, and therefore to the identification of more meaningful association between species.

Legendre & Gallagher (2001) show that a PCA conducted on data transformed using the Hellinger method (Table 2.1) produces a good representation of an ecological gradient - the distance preserved by the PCA is called the Hellinger distance and has been shown by the authors to have good statistical properties in termes of monotonicity and coefficient of determination R^2.

Table 2.1: Hellinger transformation.

X is a matrix of size nxp reporting abundance data of $j = 1...p$ species in $i = 1...n$ sites. Row sums are noted x_{i+}. The Hellinger transformation turns X into X' such as:

$$x'_{ij} = \sqrt{\frac{x_{ij}}{x_{i+}}} \tag{2.1}$$

Although transformation-based PCA has been described for species abundance data, its principles are relevant for the identification of ES bundles involving zero-inflated, skewed ES distributions.

2.4.2.2 The relevance of transformation-based PCA (tb-PCA) for ES in urban areas

Urban areas can be considered as landscapes with a strong environmental gradient, going from heavily built-up areas where natural elements are sparse to parks and other greenspaces featuring a potentially large and diverse cover of vegetation and water.
If an ES is provisioned at a high level in an area, it means that the combination of environmental parameters in that area is favourable to its provision; however, a null or low value could be due to a variety of causes, including: absence of any natural elements, presence of natural elements which do not provide the service, or presence of natural elements below the threshold required for provision to happen. As this is a description of the double-zero issue introduced above, similar conclusions follow: inferring associations among urban ES with a simple PCA may lead to potentially misleading interpretations.
Another argument for avoiding a simple PCA lies in the expected lack of meaning of the variance statistic for the services having a skewed distribution.

The alternative of tb-PCA for ES comes with limitations. The transformation preceding the PCA requires all variables to be measured on the same positive scale, which requires a pre-transformation on the ES dataset. Furthermore, (modified) profiles of relative ES values, which are obtained after transformation, have a less obvious physical meaning than for abundance data. Therefore, the process leading to tb-PCA results for ES values should probably be seen as no more than mathematical operations, transposed from a case (species abundance data) where they were grounded in physical reality.

2.4.3 Identifying ES bundles using a tb-PCA

The methodology can be divided into three steps:

1. Scaling and transforming the dataset;

2. Conducting a PCA; and
3. Conducting a hierarchical analysis on the PCA results in order to identify ES bundles.

2.4.3.1 Scaling and transforming the dataset

The transformation preceding the PCA is the Hellinger transformation, introduced in the previous section. For it to make sense, the dataset must be brought to a common, positive scale (see section 2.4.2.2). A simple method for this purpose is range standardisation (Equation 2.2):

$$r_i = \frac{x_i - min(x_i)}{max(x_i) - min(x_i)} \tag{2.2}$$

The Hellinger transformation is then conducted on the scaled dataset.

2.4.3.2 Conducting a PCA

As introduced in section 2.4.1, by performing a PCA one hopes to find a few (two or three) principal components summarising the relationships between the studied ES. The number of components to retain depends on the amount of cumulative variance explained by them, and the threshold of acceptable cumulative variance is subjective and is an ad-hoc decision. In the case of a two-dimension representation of the variables, the studied ES are represented by vectors in a 2D plane (ES-vectors), where the two orthogonal axes are the first two principal components (PC-axes). Projections of the ES-vectors on the PC-axes are proportional to the covariance of the ES with the principal components; therefore, ES-vectors having similar projections on the PC-axes can be considered as consistently associated with each other. The next step is to quantify this similarity and find groups of ES based on it, i.e. identify ES bundles.

2.4.3.3 Conducting a hierarchical analysis on the PCA results in order to identify ES bundles

The goal is to identifying clusters of services for which within-group variation of distances among ES-vectors is minimal and inter-group variation of these distances is maximal. Among available clustering methods, preference in the bundle literature for bundling services after a PCA goes to (agglomerative) hierarchical clustering. This method starts by considering every service as belonging to its own group, then at each stage fuses services or groups of services which are closest, until a single group of all services is obtained (Everitt 2011). The output of such a method is a dendrogram illustrating the partitions produced at each stage and the distances at which each fusion is made. It allows to identify clusters, called here "bundles" of services by identifying an appropriate stage for which the distance to the next fusion is large enough to consider the identified bundles as sufficiently decorrelated from one-another. Often, this is done by selecting the largest distance, but the process is subjective and another distance may be selected. Although all types of hierarchical clustering methods use the same distance measure (Euclidean), they differ in how they select the objects between which this distance is evaluated. The specific method used in bundle literature, and reported as the most efficient, is Ward's method (Everitt 2011, Legendre & Legendre 2012).

2.5 Identification of Spatial Bundles

2.5.1 Overall strategy

The aim is to identify groups of spatial units which share a similar profile of ES, i.e. which have similar values for the set of ES under consideration. A subset of clustering methods, hierarchical-based and centre-based clustering, have extensively been used in bundle literature (see section 2.2); however, their application needs to be tailored to the initial data structure and to the type of similarity to be displayed.

As a result, the bundle approach developed here consists in the following steps, which are then detailed in bespoke sections:

1. *Data transformation*:

   Data transformation can be performed when data characteristics such as skewness is likely to impact the performance of the selected clustering method, even if the method was chosen in order to have low sensitivity to such characteristics. One can also choose to transform data when one is more interested in the rank of spatial units in terms of values, and less in the disparity of values across them. However, if one wants to keep in the analysis the tendency of ES to take extreme values in some places and not others, then data should not be transformed when possible. There is sometimes, in data transformation, a compromise between clustering performance and what one wants to show.

2. *Data standardisation*:

   Data standardisation allows to compare variables measured with different dimensions and on different scales, as is the case with a set of ES. Data standardisation is essential in order to find meaningful patterns which are driven by similarity between spatial units and not by artificial factors such as measuring units.

3. *Dimension reduction*:

   In most bundle studies, clustering is performed on the full set of (transformed and) standardised data. However, partitioning methods sometimes do not perform as well in "high" dimension as they do in 2 or 3 dimensions, depending on the structure of the dataset - the so-called "curse of dimensionality". It may therefore be necessary to reduce the dataset dimension in order to optimise the performance of the methods. In the same way as data transformation, this step may not be necessary in all cases.

4. *Clustering*:

   A clustering method is applied to the (transformed and / or projected) standardised dataset. The approach developed here applies the k-medoid method as a way to identify structure in the dataset.

5. *Validation*:

   Involves assessing the quality of clustering using metrics measuring the within-cluster similarity and/or inter-cluster dissimilarity. In this approach, validation occurs twice: just before clustering in order to select the best solution in the (transformed and / or reduced) standardised space, then after clustering to compare solutions coming from different spaces, if applicable.

Knowing which combination of data transformation, standardisation, projection and clustering would give an optimal solution in terms of quality and relevance of the resulting bundles is not straightforward. Therefore, the approach includes testing different combinations. Figure 2.4 shows these combinations and the following sections describe each step.

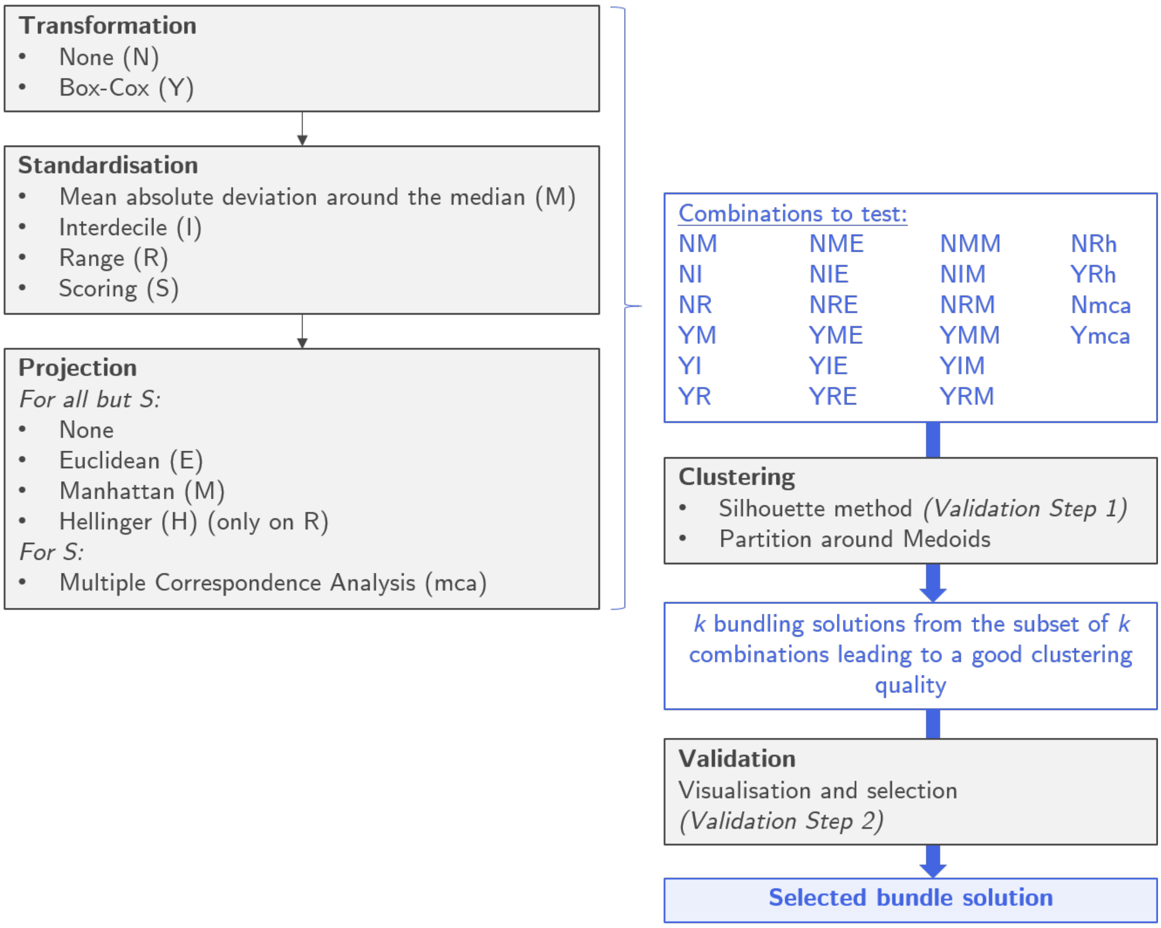


Figure 2.4: Methodological approach for identifying Spatial Bundles.

In addition to increasing the robustness of the approach, the systematic testing of all combinations brings transparency to the identification of bundles, and therefore participate in ensuring its legitimacy.

2.5.2 Data transformation

When distributions are positively or negatively skewed , it becomes difficult to detect differences between values in the bulk of the data, i.e. between smaller or larger values, respectively. In other words, most of the variance is caused by extreme values which do not represent the majority of the data. Transformation aims at reducing skewness to get closer to normality, thereby reducing differences between larger (respectively smaller) values and magnifying the differences between smaller (respectively larger) values.

Transforming right-skewed data has been done in bundle literature by applying log or square-root functions (see for instance Turner et al. (2014), Crouzat et al. (2015)), depending on the type of distributions and the extent to which they diverged from normality. However, one would expect different distribution shapes across the different ES, as they are not expected to follow similar patterns across the city; so that applying one of these methods, e.g. log-transformation, would be relevant for some variables but not the others. An alternative method more sensitive to this issue is the *Box-Cox transformation* (Gale et al. 2016, Box & Cox 1964), which turns the values of ES x_i into y_i such as:

$$y_i(\lambda) = \begin{cases} \dfrac{x_i^{\lambda} - 1}{\lambda} & \text{if } \lambda \neq 0, \\ log(x_i) & \text{if } \lambda = 0 \end{cases} \tag{2.3}$$

Where λ is a value which gives a transformed distribution as close to normality as possible. In practice, all possible values of λ in a specific range are tested and the optimal value for the ES considered is selected. This 'optimal value' is the one which results in the best approximation of a normal distribution curve, as measured by the Shapiro-Wilk test. If that value happens to be zero, then a log-transformation is applied. This original Box-Cox transformation is only valid for strictly positive data, which is an issue for ES which can take a value of zero. Nevertheless, it is possible to circumvent this limitation by adding a constant c to the data:

$$y_i(\lambda, c) = \begin{cases} \dfrac{(x_i + c)^{\lambda} - 1}{\lambda} & \text{if } \lambda \neq 0, \\ log(x_i + c) & \text{if } \lambda = 0 \end{cases} \tag{2.4}$$

One simple practice, based on empirical experience, is to assign to c the second smallest value after zero, divided by two (Dormann 2009).

Box-Cox can also be applied to left-skewed data after they have been "mirrored" into right-skewed data. Transformed data is then obtained by mirroring again the Box-Cox result:

$$x_i^{(m)} = x_{i,max} - x_i + x_{i,min}$$
$$y_i(\lambda, c) = \begin{cases} -\dfrac{(x_i^{(m)} + c)^{\lambda} - 1}{\lambda} & \text{if } \lambda \neq 0, \\ -log(x_i^{(m)} + c) & \text{if } \lambda = 0 \end{cases} \tag{2.5}$$

However, it can be argued that distribution skewness should be kept, as it contains information about how ES are distributed across the city - namely that there are some places in which they take extreme values. Therefore, the approach recognises that transformation should not be automatic and proposes testing two transformation strategies:

1. No transformation
2. Box-Cox transformation

Transformed or non-transformed data is then subject to standardisation.

2.5.3 Data standardisation

Data standardisation allows to compare variables measured with different dimensions and on different scales and is an essential step before applying hierarchical or centre-based clustering. The bundle approach developed here tests four standardisation methods:

1. Median-based z-score
2. Range scaling
3. Interdecile scaling
4. Ordinal scoring

The first three methods are commonly used in preparatory steps before clustering analyses (see for instance Crouzat et al. (2015), Yang et al. (2015), van der Zanden et al. (2017), but also Gale et al. (2016)). The fourth method is normally used to build ordinal indicators and has not been used before as a preparatory step to bundling. It is introduced here in order to test its ability to help clustering analyses deal with highly skewed datasets.

The following paragraphs present the four methods.

Median-based z-scores use the median and the mean absolute deviation around the median (MAD) in order to standardise data (Equation 2.6). It expresses raw data in terms of the number of MAD they are away from the median. All standardised variables have a MAD of 1 and a median of zero.

$$z_i = \frac{x_i - median(x_i)}{MAD(x_i)} \tag{2.6}$$

Median-based z-scores are an alternative to the original z-scores, which use mean and standard deviation (i.e. absolute deviation around the mean) to scale data. They were preferred to original z-scores because median-based statistics are more robust to describe skewed, possibly zero-inflated distributions, than mean-based statistics.
Data scaled using this method will retain its extreme values, which can be both an advantage and disadvantage, as mentioned earlier. Indeed, this allows to keep information about specific cases, but can be at the expense of the performance of clustering algorithms.

Range scaling is the most commonly used standardisation method in bundle literature (original z-scores come second). It compresses values into the range of 0 to 1 (Equation 2.2), thereby reducing the impact of extreme values in addition to putting all variables in the same scale. By reducing the differences of variation across the variables, using range standardisation results in the loss of some information about specific cases and can lead to omission of interesting patterns in data. However, it may enable one to focus on more essential and general similarities and dissimilarities across variables.

The third standardisation method included in the optimisation process is *interdecile standardisation*. It is a variant of range standardisation, in which the data is scaled over a smaller range, between the 90^{th} percentile and the 10^{th} percentile (Equation 2.7).

$$d_i = \frac{x_i - median(x_i)}{perc_{90\%}(x_i) - perc_{10\%}(x_i)} \tag{2.7}$$

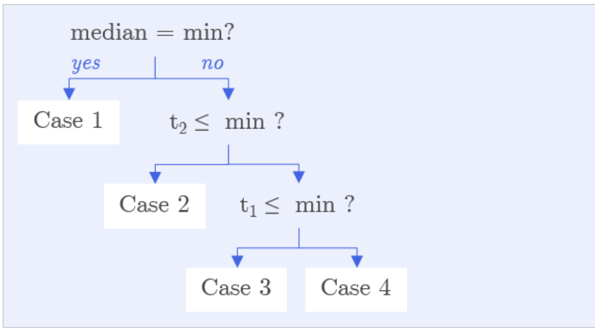
This method is selected because it has been shown to have a good performance in data preparation for clustering and was used in the 2011 OAC (Gale et al. 2016). It allows to overcome the compression disadvantage of range standardisation while still reducing the impact of extreme values.

The fourth standardisation method, *ordinal scoring*, scales data into scores from 1 to n. In order not to define n arbitrarily, the least variant variable is considered and the number of MAD over which it spans is chosen for n. Then the threshold values for assigning data to either of the n categories are defined for each variable in relation to its median and the MAD. Different cases are possible depending on the how data is distributed around the median (Figure 2.5 gives an example for $n = 5$)

(a) Thresholds for score assignment

$$
\begin{aligned}
t_1 &= \text{median - 1.5 mad}\\
t_2 &= \text{median - 0.5 mad}\\
t_3 &= \text{median + 0.5 mad}\\
t_4 &= \text{median + 1.5 mad}\\
t_5 &= \text{median + 2.5 mad}\\
t_6 &= \text{median + 3.5 mad}
\end{aligned}
$$

(b) Determining the relevant set of thresholds



(c) Conditions for score assignment. "x" refers to ecosystem service value.

Score	Case 1	Case 2	Case 3	Case 4
1	$x < t_3$	$x <$ median	$x < t_2$	$x < t_1$
2	$t_3 \leq x < t_4$	median $\leq x < t_3$	$t_2 \leq x < t_3$	$t_1 \leq x < t_2$
3	$t_4 \leq x < t_5$	$t_3 \leq x < t_4$	$t_3 \leq x < t_4$	$t_2 \leq x < t_3$
4	$t_5 \leq x < t_6$	$t_4 \leq x < t_5$	$t_4 \leq x < t_5$	$t_3 \leq x < t_4$
5	$x \geq t_6$	$x \geq t_5$	$x \geq t_5$	$x \geq t_4$

Figure 2.5: Process for assigning scores to intervals of data using thresholds based on the median and the mean absolute around the median. Different cases are defined depending on the relationship between pre-defined thresholds (a) and the minimum vale across all spatial units (b). Each case differs in the selection thresholds which are relevant for it (c).

Ordinal scoring is a severe way to compress extreme values and reduce differences of variation across the variables, therefore sharing range standardisation's advantages and limitations. Furthermore, the method assigns a value of 1 to low values without distinguishing between zeroes and non-zeroes, which on the one hand allows to mitigate the impact of zero-inflated distributions; but on the other hands risks erasing differences between different levels of low provision of services.

Clustering can be performed directly on the standardised dataset, or a projection of this dataset in lower dimension.

2.5.4 Dimension reduction

The scaled dataset is projected onto a set of axes which represent a decreasing amount of its variance. The projection is such that the distance between the spatial units, in terms of ES values, are preserved. Then, only the first two or three axes are kept and the coordinates on this axes form the new values for each spatial unit. The choice between two or three depends on the extent to which two axes contain enough information about the original dataset. Reducing the dimension of a dataset can improve the quality of clustering, i.e. it can reveal structure in a dataset, that is otherwise masked in higher dimension; however, this is not always the case as there can be meaningful structure linked to lower variance components.

For continuous data, i.e. data stemming from the median z-scores, range or inter-decile standardisation, Multi-Dimensional Scaling (MDS) is used for projection. The bundle approach developed here tests two distance measures: Euclidean and Manhattan. The Hellinger distance is also tested for range standardised datasets.

- When the distance preserved is Euclidean, MDS is equivalent to performing a PCA. Euclidean distance is the most intuitive and commonly used distance measure. However, it is sensitive to the presence of extreme values: for instance, if two spatial units are close on most ES, but discrepant on one of them, this last variable will influence a lot the distance value compared to the role of the other variables.

- The Manhattan distance between two spatial units is the sum of the absolute differences of their values. This distance is more robust to the presence of extreme values: in the previous example, the use of a Manhattan distance will be less influenced by the discrepant value than the Euclidean one. Considering this distance in the bundle approach is therefore relevant, since highly skewed variables are expected.

- The Hellinger distance was introduced in section 2.4.2. It can only be applied to the range standardised datasets.

For datasets scaled with ordinal scores, the counterpart of PCA for such data is used. This method is called Multiple Correspondence Analysis (MCA) and allows to represent categorical data in lower dimension.

Following projection, or directly after standardisation, the datasets are subject to a clustering analysis. In this approach, to simplify the procedure, datasets standardised with ordinal scores always go through a projection step before clustering. Choosing otherwise would require to develop a distance measure fitting the categorical dataset prior to clustering, an endeavour which is beyond the scope of the thesis.

2.5.5 Clustering

There are many ways of categorising clustering techniques. To provide the rationale for choosing a k-medoid method in this approach, I am making the difference between so-called 'nested' and 'flat' partitioning:

- Hierarchical clustering, which was introduced in sections 2.2 and 2.4, produces a nested set of partitions by merging (or splitting) groups in a step-by-step sequence. The decision at each step is based on the similarity between the elements or groups to merge (or split). One then has to decide at which level of merging (or splitting) to divide the nested partitions into clusters of objects (here spatial units).
- Flat partitioning finds all clusters at once by considering clustering as an optimisation problem. Methods in the scope of this thesis seek to find k clusters by minimising the difference between objects and their cluster centres. Given a number k, many combinations of centres and partitions are tested by the clustering algorithm in order to find a minimum to the function representing the

difference measure (Everitt 2011, Legendre & Legendre 2012).

Technically, bundling spatial units can be done with either type of methods. Conceptually however, bundling is closer to flat partitioning: we are more interested in finding spatial units bound by their similarity to a common 'typical' unit rather than identifying bundles from a classification.

The specific method used in this approach is the Partition Around Medoids (PAM), which is based on the identification of representative spatial units (the 'medoids'), which are then used to construct bundles by assigning each spatial unit to its nearest medoid (Rousseuw & Kaufman 2005). Although k-means is the most widespread flat partitioning method across bundle literature (see section 2.2), PAM is preferred in this approach for two reasons:

1. PAM tends to be more robust than k-means: while k-means aims at minimising the total squared error between objects and their centres, PAM aims at minimising the sum of dissimilarities, which makes it less sensitive to extreme values.

2. PAM and k-means both give bundles characterised by their members and their centroid. A bundle centroid from the k-means method would be the mean of ES values exhibited by spatial units belonging to the bundle, while the centroid (medoid) from the PAM method is an actual spatial unit. Interpretation of results then becomes more meaningful, for instance for comparing the different identified bundles.

The number of bundles has to be provided as an input to the PAM method. In order to determine an adequate number, the Silhouette method is applied (Rousseeuw 1987). This method is a measure of the degree of membership of a spatial unit to its bundle, based on the average dissimilarity between this unit and all units in the bundle to which it belongs, compared to the same measure computed for the next closest bundle. This measure ranges from -1 to 1 and is called Silhouette width -

the higher the width value, the better the spatial unit is clustered; in particular, a negative value suggests the corresponding unit may have been placed in the wrong bundle. The Silhouette method applied to the problem of determining an adequate number of bundles will compute the average Silhouette width for different numbers of bundles. The solution with the highest average width is considered the one offering the best partition; however, the clearest partition may not be the best bundle solution. In particular, a two-bundle solution will not provide much details about ES patterns across the landscape, even if it is the solution with the highest average width.

Rousseeuw & Kaufman (2005) have identified the value of 0.50 as being the approximate threshold above which one can consider a reasonable structure to have been found in the data; a value they derived empirically, using their in-depth experience of the Silhouette method. This threshold is used here as a validation step: if the best solution for a dataset is found to have a lower average width than 0.50, it is considered that no meaningful bundles have been found for the space the clustering is taking place. Therefore, only datasets for which solutions over 0.50 exist are effectively clustered and go through the following validation phase.

2.5.6 Visualisation and Validation

Bundles of the solutions which passed the previous validation step are graphically represented in terms of the levels of provision of ES in each bundle. The bundles are also represented in a map, where all spatial units belonging to the same bundle are shown in the same colour.

The selection of the bundle solution which is the most appropriate for the landscape under study may depend on the objective: what do we want to show with the bundling? Do some partitions reveal patterns that are more useful than others? On-the-ground knowledge of the study area is also a factor helping to identify the most meaningful solution.

2.6 Analysis of bundles

2.6.1 Assessing the strength of associations among ecosystem services

In the bundle literature, the strength of associations among ES has been assessed by computing pair-wise correlations: the higher the correlation between two services, the stronger their association. Correlation coefficients can be computed using the Pearson, Spearman or Kendall method: Pearson coefficient measures the linear dependence between two variables, while Spearman and Kendall coefficients work on ranks and are a measure of monotonic dependence (Freedman et al. 2014, Corder & Foreman 2014).

In this bundle approach, measuring the strength of associations using the Pearson correlation could lead to misleading results because of the expected presence of extreme values for some of the services. To illustrate the issue, let us consider two pairs of services differing by only one extreme value - (x1, y1) and (x2,y2) in Figure 2.6. We want the measure of association strength to yield a similar result for both pairs, as the situation they represent is the same but for one spatial unit. However, the Pearson correlation coefficient is higher for the pair featuring an extreme value, because a linear model fits this pair better. Misleading results of this sort would be possible with the types of datasets expected; therefore, Pearson correlation was not considered an adequate measure of the strength of association between two services.

Rank correlation coefficients are robust to the presence of extreme values (see example in Figure 2.6). One issue encountered with rank-based correlation is the management of ties, which is relevant to this bundle approach because of the expected presence of double-zeroes. The correlation coefficient which most robustly deals with ties is Kendall τ_b, which was therefore selected as the measure of association strength between the services.

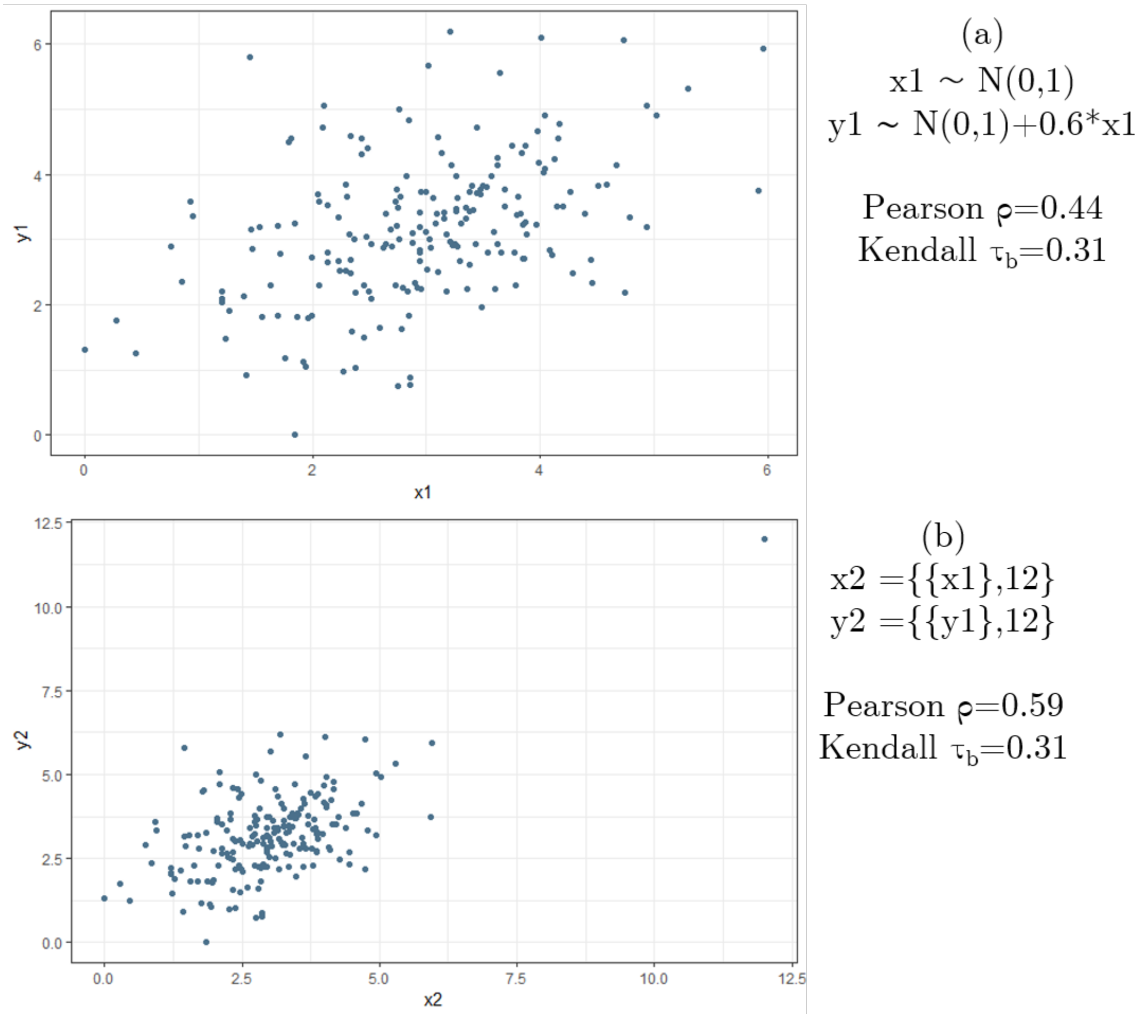


Figure 2.6: Example showing the lack of robustness of the Pearson correlation coefficient to the presence of extreme values in a dataset. Panel (a) shows the scatter plot, Pearson and Kendall correlation coefficients of two randomly-generated normal distributions x1 and y1. Panel (b) shows the scatter plot, Pearson and Kendall correlation coefficients of x2 and y2, variables differing from x1 and y1 by one extreme value. Correlation between x2 and y2 as measured by the Pearson coefficient (symbol ρ) is higher than the one measured for (x1,y1), Kendall τ_b stays the same.

2.6.2 Identification of Spatial Bundles' drivers

Using regression analyses, the objective is to find a set of factors which are able to predict the assignment of spatial units to their bundle. In accordance with recommendations from Mouchet et al. (2014), Spake et al. (2017), drivers are identified by studying the influence of pre-selected socio-ecological parameters on bundle results. The list of relevant parameters is set using expert knowledge and hypotheses derived from a qualitative interpretation of bundle maps and plots.

First, *Multinomial Logistic Regression* (MLR) is used to predict the probabilities of outcome of the different bundles, given a set of pre-identified parameters. MLR is an extension of logistic regression for cases where the dependent variable has more than two possible outcomes (Menard 2002). The pre-identified parameters are iteratively dropped from the model in order to find the optimal set of factors giving an appropriate level of prediction. The prediction accuracy is evaluated by conducting the regression on a training set and applying the result on a testing set (Hastie et al. 2009): the level of accuracy is defined by the ratio of spatial units correctly assigned to their bundle over the total number of spatial units in the testing set.

The robustness of the prediction is evaluated by conducting a *Classification And Regression Tree analysis* (CART), using the optimal set of factors identified by the MLR. The CART method builds a decision tree by splitting on the values of the predictors: the leaves represent bundle outcomes and the branches the conjunctions of predictor values leading to these outcomes (Breiman et al. 1984). To build the three, CART tries to split the data into subsets so that each subset is as homogeneous as possible; it then derives the threshold values from its splits. If the number of splits is too low, the model will be too simple and the accuracy poor; but if the number of splits is too high, then overfitting will occur. To control this parameter, a k-fold cross validation method can be used, which optimises the model by compromising between simplicity and overfitting (Fossati 2015). The CART method is applied on a training set and its prediction accuracy is assessed using a testing set.

Because MLR and CART use different regression methods, factors accurately predicting bundle formation in both analyses can be more confidently characterised as drivers. Furthermore, CART's visual tree - showing threshold values for assigning spatial units - offers an interpretable output by providing a decision tree for bundle assignment based on driver values.

2.7 Summary

This Chapter presents methods to identify and analyse both ES Bundles and Spatial Bundles from a dataset reporting ES values for all spatial units in a given study area.

A systematic review of existing practices shows that there is no one-size-fits-all approach for identifying and analysing bundles. In this study, the choice of methods builds on existing practices and the expected structure of the dataset, characterised by highly skewed spatial distributions of services.

ES Bundles are detected with a transformation-based PCA to circumvent issues linked to the expected zero-inflation of the distribution of ES relevant to this study. For Spatial Bundles, a six-step methodology based on k-median clustering analysis was designed.

Considerations of credibility and legitimacy aspects were instrumental in designing the approach: credibility was sought by efforts to address the methodological shortcomings of previous studies, while it is hoped that this Chapter is transparent enough to bring legitimacy to it. Salience played a less important role than credibility and legitimacy in developing the approach, which aims to be general enough to be adapted to different contexts and decision-making objectives.

Its application to the case study is described in Chapter 3.

Chapter 3

Implementation of a bundle approach

3.1 Introduction

This Chapter describes the implementation, in the City of Edinburgh, of the bundle approach developed in Chapter 2.

The next two sections delineate the scope of the implementation. Section 3.2 defines the scale and extent of the study area with criteria based on salience to urban strategic decision-making, while section 3.3 identifies relevant ES by considering the contribution of urban natural spaces to issues of well-being and sustainability.

Section 3.4 presents the specific methodology used to quantify the selected services, following the strategy defined in Chapter 2. Emphasis is placed on the publicly-accessible, and recognised, nature of data sources - both for spatial data and the empirical studies used to derive ES values from them. The individual maps of the selected services are also presented in this section.

Sections 3.5 and 3.6 show results obtained from the application of bundling methods to identify ES Bundles and Spatial Bundles, respectively. Drivers behind the patterns evidenced by the two types of bundles are investigated in section 3.7.

3.2 Geographical scope: scale and extent

The scale at which the ES are assessed influence the patterns likely to be detected in a landscape, which makes the choice of scale especially important for a spatial bundle study. In the bundle literature, there are cases made for both the use of administrative and fine-scale units as scales of assessment (Saidi & Spray 2018). Administrative scales provide high-level overviews of ES patterns, using geographic delineations commonly used for decision-making purposes. Bundle identification at that scale would therefore allow to investigate the research aims of this thesis, which focus on high-level long-term and medium-term visions and strategies. Nevertheless, administrative scales do not fully reflect the heterogeneity of the landscape and the locally-meaningful patterns which can be identified at a higher resolution. In order to limit the loss of information that occurs when assessing bundles at that scale, the highest administrative resolution available in Scotland, the so-called *data zone*, is selected. Data zones are the key geography for the dissemination of small area statistics in Scotland and are widely used across the public and private sector. They are designed to have roughly standard populations of 500 to 1,000 household residents, nest within Local Authorities, and have compact shapes that respect physical boundaries where possible (Scottish Government 2019*a*).

There are 597 data zones inside the official boundaries of the City of Edinburgh. However, these boundaries encompass areas beyond the bypass in the Western part of Edinburgh, which are managed differently when it comes to greenspaces[1]. Therefore, only the area included within the City bypass was selected for the project, leading to a total of 558 data zones for a $118km^2$ area, i.e. a resolution of $4.7km^{-2}$. (Figure 3.1). 555 data zones are classified as belonging to "Large Urban Areas Settlements of over 125,000 people" and 3 as belonging to "Other Urban Areas Settlements of 10,000 to 125,000 people" according to the Scottish Government Urban Rural Classification

[1] Personal communication with the Manager of the City's Parks & Greenspace service

(Scottish Government 2019b).

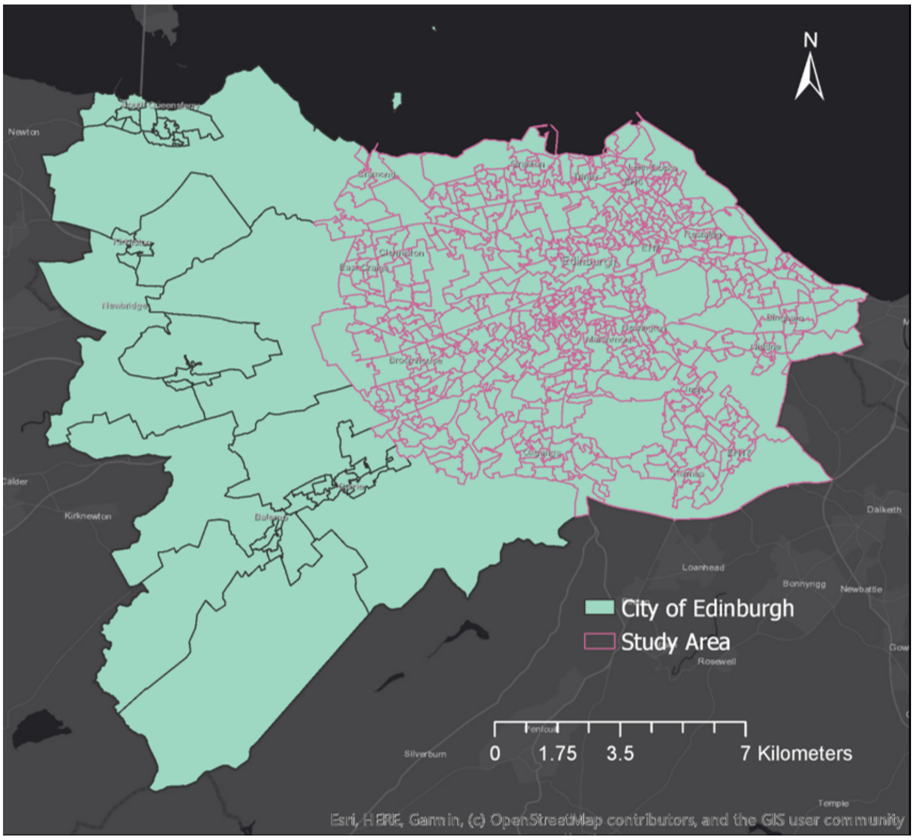


Figure 3.1: Map of the data zones included in the study area.

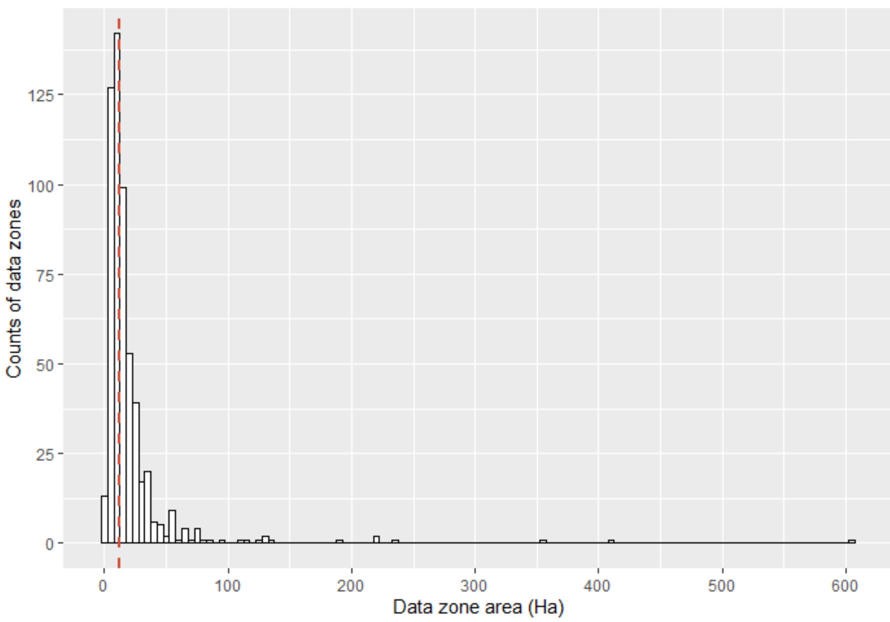


Figure 3.2: Distribution of data zone sizes within the study area. The red dotted line indicates the median size

The size of data zones within the study area vary from 0.937ha to 604ha, with a mean at 21.1ha and a median at 12.3ha (Figure 3.2). Most data zones are smaller than 50ha but there are a few extreme cases spanning from 100ha to 600ha. Figure 3.1 suggests that these large data zones delineate large parks, golf courses and agricultural-related areas. As a result, the bundle assessment conducted in this Chapter will not be able to reflect patterns within such locations.

3.3 Identification of relevant ecosystem services

Relevant ES were selected based on their role in addressing the main issues affecting well-being in cities. These issues were identified in the literature and validated with the manager of the Greenspace service. The same process was applied for the identification of relevant ES.

3.3.1 Issues affecting well-being in cities in the developed world

Historically, improvements in education, housing, and public health have resulted in longer life expectancy and healthier populations in cities. However, as infectious diseases and malnutrition declined, non-communicable diseases, including physical and mental illness, became more prevalent (Vardoulakis & Kinney 2019). Three main issues have led to this situation: environmental pollution, extreme weather events, and lifestyles characterised by sedentarism, unhealthy diets and stress (Friel et al. 2011, Prüss-Ustün et al. 2019, World Health Organization 2017).

3.3.1.1 Environmental pollution

Urban transportation, domestic heating and industrial activities emit particulate and gaseous air pollutants which seriously affect the well-being of city residents (Karagulian et al. 2015, Mcdonald 2012). Exposure to poor air quality leads to respiratory and cardiovascular diseases and has been identified as the largest environmental risk for global health (World Health Organization 2016). For instance, the estimated cost of the overall health impact of air pollution in the UK is £54 billion a year, accounting for 3.7% of the Gross Domestic Product (WHO Regional Office for Europe 2015).

Noise has also been identified as a major environmental health problem in Europe, including in cities, where traffic is the main source of pollution (Peris 2020). Close to half of the European urban population (43%) is exposed to traffic noise levels likely to adversely affect their well-being and health. Noise pollution has been linked to auditory and non-auditory effects, including increased risk of hypertension, impaired cognitive development in children and psychological stress (Science for Environment Policy 2015): for instance, loss of healthy life due to UK noise exposure was valued at £1.09 billion (Harding et al. 2013).

3.3.1.2 Extreme weather events

Urban residents are exposed and vulnerable to extreme weather events, the intensity and frequency of which are exacerbated by climate change. These events, namely floods, heatwaves and droughts, are associated with an increasing rate of mortality and economic losses (Elmqvist et al. 2019).

→ Floods
Cities' vulnerability to floods comes from their large impermeable surface area, which leads to a lack of infiltration causing high volumes of surface water runoff: for instance, urban landscapes with 50–90 % impervious cover can lose 40–83 % of rainfall to surface runoff (Elmqvist et al. 2013). This comes with risks of sewer overflow, street pollutant wash-off and obstruction of groundwater recharge. Possible consequences include loss of life, damage to homes and businesses and disruption of basic services such as supply of drinking water and electricity as well as wastewater management. In the UK, if

current levels of adaptation continue, Expected Annual Damages (EAD) are projected to increase significantly by 2080s - the projected increases are 50% under the 2°C climate change projection and 150% under 4°C climate change projection, with an increase in risk when projections of population growth are included (Sayers et al. 2015).

→ Heat waves

Climate change is expected to lead to an increase in the frequency and intensity of heat waves (IPCC 2012). Heat waves are especially pronounced in cities because of the so-called urban heat island effect (UHI), a phenomenon whereby cities exhibit higher temperatures than rural or suburban surroundings, due to a combination of factors including high-energy use, densely built structures and large areas of heat-absorbing surfaces (Mohajerani et al. 2017). For instance, UHI intensity (defined as the difference in air temperature between built up urban areas and rural locations) can reach values of up to 10 °C in large cities, such as Manchester (Smith et al. 2011). Heatwaves such as that in 2003 which led to approximately 2000 excess deaths in the UK, 14,802 in France, and 70,000 across Europe, are predicted to become typical of summer by the 2040s (Taylor et al. 2015, Le et al. 2014). It is therefore likely that with constant or increasing urbanisation, the associated health risks will continue to be a cause for concern for the UK public health sector (Heaviside et al. 2016).

→ Droughts

Climate change is likely to bring drier summers and increased uncertainty regarding rainfall, including in the UK: for instance, predictions for Scotland suggest a decrease in summer rainfall of 10-20% by 2050 (SEPA 2015). This would exert an increasing pressure on water users, in particular urban ones, with potential shortages or limited authorised use of water. The severity of impacts linked to decreased rainfall will depend on the resilience of water systems and available storage.

3.3.1.3 Lifestyles characterised by sedentarism, unhealthy diets and stress

Living in an urban environment is long known to be a risk factor for mental health issues such as depression (Mazda 2011). This is true even though infrastructure, socioeconomic conditions, nutrition and health care services are better in cities than in rural areas. Social stress may be the most important factor for the increased risk of mental disorders in urban areas. It may be experienced as social evaluative threat, or as chronic social stress, both of which are likely to occur as a direct consequence of high population densities in cities. Social disparities also become much more prominent in cities and can impose stress on the individual. In addition to mental health and well-being, improving participation in health-enhancing physical activity has become a public health issue of urgent concern (Edwards, Peggy; Tsouros 2008). Regular physical activity contributes to the prevention and management of over 20 conditions that are major costs to the National Health Service including coronary heart disease, diabetes, obesity and certain types of cancer (Davies et al. 2011).

3.3.2 Relevant issues affecting urban sustainability

Two major environmental issues, which are not directly related to urban well-being, were identified as relevant with regards to the potential of urban nature to address them: the emissions of greenhouse gases and the loss of biodiversity. The relevance of these challenges was highlighted by the manager of the Greenspace service.

3.3.2.1 Emissions of greenhouse gases

The world's cities are responsible for up to 70% of the global emissions of greenhouse gases – not counting indirect emissions associated with goods and services consumed by cities (food, clothing, electronics, air travel, construction materials) (UN Habitat 2011, C40 Cities 2018). Cities are therefore a major contributor to global climate change. Urban greenhouse gases emissions mainly stem from transportation, direct fuel combustion, the consumption of energy for lighting, heating and/or cooling, as well as the treatment of waste (UN Habitat 2011).

3.3.2.2 Lack / Loss of biodiversity

Urbanisation is a cause of decline in native species because of habitat loss, fragmentation, and the introduction of invasive species which can lead to the homogenisation of biological communities (Beninde et al. 2015). As such, it is one of the main drivers for the decline in biodiversity worldwide, along with agricultural conversion. For instance, a study analysing the global impacts of urbanisation on biodiversity found that the density of bird and plant species has declined substantially: only 8% of native bird and 25% of native plant species are currently present compared with estimates of non-urban density of species (Aronson et al. 2014). However, the same study also found that few birds and plants are cosmopolitan and that each city reflects the unique biotic heritage of its geographic location. Furthermore, it appears that moderate levels of urbanisation, for instance in suburban areas, can actually support biodiverse communities (McKinney 2008) notably through the provision of a variety of small-scale habitats (private gardens, parks, roadside verges, allotments, vacant lots,. . .). Biodiversity is paramount in the city because it supports the capacity of urban greenspaces to tackle the challenges detailed above (adverse environmental events and nuisances, barriers to staying healthy in the city, emissions of greenhouse gases). A biodiverse ecosystem is indeed indicative of its health and therefore of its potential to contribute to people's well-being – the challenge for the city lies then in its capacity to support and enhance its biodiversity.

3.3.3 The contribution of natural spaces to well-being: identification of relevant ecosystem services

Natural spaces can help to prevent and / or mitigate the five issues introduced above: environmental pollution; extreme weather events; lifestyles characterised by sedentarism, unhealthy diets and stress; emissions of greenhouse gases; and lack / loss of biodiversity. Natural spaces refer here not only to formal greenspaces, but also to any area covered by vegetation or water – even if not technically a greenspace. This section identifies the ES they provide, that contribute to addressing the five main issues described previously: the following paragraphs describe the rationale for including the services listed in Table 3.1.

Table 3.1: Ecosystem services selected in the study

Contribution of natural spaces to well-being	Selected ecosystem services
Prevention or mitigation of extreme weather events	Run-off retention Temperature regulation
Mitigation of environmental pollution	Air purification Noise attenuation
Mitigation of greenhouse gases emissions	Carbon storage
Prevention and mitigation of the loss of biodiversity	Habitat provision
Improvement of physical and mental well-being	Contribution to physical activity Contribution to mental health Food growing

3.3.3.1 Contribution to the prevention or mitigation of extreme weather events

→ Issues linked to water quantity and quality

Natural spaces can reduce pressure on conventional urban drainage systems by decreasing water flow and removing pollutants, thus reducing urban vulnerability to floods and reduced water quality (EU WFD CIS Working Group Programme of Measures 2014). Having an adequately designed greenspace system helps cities to continue offering basic services such as wastewater management when grey infrastructure reaches its limits - it is also an effective alternative to environmentally- (and sometimes economically-) costly grey infrastructure (Pataki et al. 2011, McPhearson et al. 2015). The run-off retention services offered by natural spaces can also allow for an increased groundwater recharge during wet periods and thus help prepare for dry spells.

Run-off Retention is therefore selected as an ES contributing to addressing issues linked to water quantity and quality. Vegetation reduces surface runoff following precipitation events by intercepting water through the leaves and stems, to later evaporate or gradually become released to the ground as stem flow or through fall (Derkzen et al. 2015, Elmqvist et al. 2013). Rainfall also directly infiltrates the permeable soil underneath vegetation; the soil then acts as a sponge by storing water in the pore spaces until it percolates as through-flow and base-flow. These two processes slow down peak flow, reduce runoff volume, remove pollutants and release rainwater more steadily. Street trees in New York, for instance, intercept 890 million gallons of stormwater annually (Peper et al. 2007); other means of reducing urban stormwater runoff include linear features (bioswales), green roofs and rain gardens: for example, green roofs can retain 25–100% of rainfall, depending on rooting depth, roof slope, and the amount of rainfall (Elmqvist et al. 2013). Factors influencing the runoff regulation function are intensity and duration of precipitation events, climate, slope, and vegetation characteristics. Trees are found to contribute largely through interception, especially when large and evergreen, while grass absorbs most of the rainwater trough infiltration (Armson et al. 2013). Water bodies support this service through their storage capacity.

→ Issues linked to heat waves and the urban heat island effect
Urban greenspaces provide a cooling effect at local to regional scales that moderates the urban heat island effect, thus enhancing human comfort and reducing energy demand (Aram et al. 2019, eftec 2018*a*). When heat waves happen, the presence of urban greenspaces ensures everyone can still benefit from living in comfortable temperatures. Cooling is considered as a critical urban ES because it cannot be imported and must be locally produced by ecosystems (McPhearson et al. 2015).

Temperature Regulation is therefore selected as the ES contributing to addressing issues linked to heat waves and the urban heat island effect. Urban greenspaces regulate local temperatures, strongly influencing urban microclimates: water areas buffer temperature extremes by absorbing heat in summertime and by releasing it in wintertime, while vegetation reduces temperature in the hottest months through shading, evapotranspiration and alteration of air movement (Davies et al. 2011, Derkzen et al. 2015, Elmqvist et al. 2013). Evapotranspiration and shading contribute most to the cooling effect:

- Water from plants absorbs heat as it evaporates, thus cooling the air in the process: for instance, one large tree can transpire 450 litres of water per day, consuming 1,000 megajoules of heat energy to drive the evaporation process (Davies et al. 2011, Elmqvist et al. 2013).
- Whereas all vegetation types provide regional cooling through evapotranspiration, trees also provide local cooling through shading. By reflecting solar radiation, they shade surfaces such as streets and sidewalks, which would otherwise absorb

heat.

Cooling by urban greenspaces depends on background temperatures; the greatest cooling is provided on hot days. Vegetated patches have a cooling effect of 1-4°C that lessens with increasing distance (noticeable up to a few hundred meters for small greenspaces) and depends on surface area, vegetation type, and spatial conjunction (eftec 2018*a*). The cooling effect of herbaceous plants occurs mostly in smaller patches and not so much in park lawns because short grasses tend to heat up more easily.

3.3.3.2 Contribution to the mitigation of environmental pollution

→ Air pollution

Vegetation can aid the regulation of air quality by acting as a deposition sink for atmospheric pollutants including ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and particulate matter less than 10 microns (PM_{10}) (Davies et al. 2011, Elmqvist et al. 2013).

Air Purification is therefore selected as the ES contributing to addressing issues linked to air pollution. Vegetation removes particles from the atmosphere by filtering them out with their leaves; tree canopies capture particles more effectively than any other vegetation type due to their greater surface roughness, which increases turbulent deposition and impaction processes (Davies et al. 2011, Elmqvist et al. 2013). Furthermore, street trees intercept more particles than more distant vegetation due to their proximity to traffic and therefore to higher concentrations of pollutants (Tallis et al. 2011, Vos et al. 2013) Performance of pollution removal also follows daily variation because during the night the plant stomata are closed and do not absorb pollutants; they also have a monthly variation because of the changes in light hours and because of the shedding of the leaves by deciduous forest during the winter (Elmqvist et al. 2013).

→ Noise pollution

The presence of adequate urban greenspaces, in particular in terms of location and density – helps protect urban environments from the noise disturbance caused by traffic and construction (Fang & Ling 2005, Van Renterghem et al. 2012). Along with measures of traffic reduction (lowering the speed limit, promoting electrical vehicles), they provide an alternative to artificial techniques such as noise-reduction barriers.

Noise Attenuation is therefore selected as the ES contributing to addressing issues linked to noise pollution. Urban greenspaces act as a natural sound buffer by attenuating noise pollution through absorption, deviation, reflection, and refraction of sound waves (Fang & Ling 2005). For instance, in row plantings of trees, sound waves are reflected and refracted – dispersing the sound energy through the branches and trees. Urban greenspaces also provide indirect noise reduction services by lessening wind speeds and allowing the presence of pervious soils (Derkzen et al. 2015). Furthermore, urban greenspaces have been proved to offer noise reducing services via psychological effects, for instance by providing sounds such as bird singing, that mask disturbing background noise (Irvine et al. 2009). Empirical research has found that vegetation factors important for noise reduction include density, width, height and length of the tree belts as well as leaf size and branching characteristics (Elmqvist et al. 2013). For instance, broadleaved trees absorb noise more effectively than coniferous trees and dense vegetation is much more efficient in lowering noise levels than dispersed vegetation (Fang & Ling 2005). Other factors influencing the level of noise reduction include the distance to the source and the frequency of noise emissions, which changes with traffic intensity (Chaparro & Terrasdas 2009).

3.3.3.3 Contribution to the prevention and mitigation of greenhouse gases emissions

There appears to be conflicting evidence on the potential importance of the role of urban greenspaces in reducing the carbon budget of cities. On the one hand, existing knowledge suggests that the contribution of urban greenspaces in reducing the carbon budget of cities may be small. For instance, around 1% of demand for carbon sequestration is met by trees in cities (Baro et al. 2017, Zhao & Sander 2015, Velasco et al. 2016), without counting greenhouse gases emitted during other steps of the life cycle like construction of greenspaces or maintenance operations. In this regard, a carbon footprint analysis of urban greenspaces conducted in Leipzig found that the design of greenspaces greatly influenced their capacity to sequester carbon (Strohbach & Haase 2012).

In contrast, other studies have highlighted the capacity of urban trees and soils to act as a carbon sink (although it ultimately depends on number, size and age of the city trees, and on soil type and history). For instance, a study conducted in London found that city trees can potentially store carbon at levels comparable to tropical forests (Wilkes et al. 2018). The value of the carbon storage service provided by urban trees in Edinburgh and Glasgow was valued at £40 million and £39.5 million respectively (Forest Research 2013, Doick et al. 2017); in inner London, carbon in the current tree stock is worth £30.9 million (£116 million in outer London) (Rogers, K., K. Sacre, J Goodenough 2015). Urban soils have also been found to hold large amounts of carbon (Pouyat et al. 2003, Edmondson et al. 2012, Lorenz & Lal 2015), although the complex and disturbed nature of urban soils makes it difficult to quantify this stock.

Considering the uncertainties linked to the contribution of urban vegetation to the net carbon flux in the city, as well as the existing evidence showing this contribution might be small, only *Carbon Storage* is selected as the ES provided by urban vegetation towards the mitigation of greenhouse gases emissions (see also Derkzen et al. (2015) for a similar choice). The choice of only considering carbon storage will not be able to reflect the direct mitigation of these emissions, as it is not a flux, but will rather act as a proxy in showing the benefits of vegetation as a carbon sink.

3.3.3.4 Contribution to the prevention and mitigation of the loss of biodiversity

Natural spaces contribute to halting the loss of biodiversity by providing habitat to potentially a wide diversity of species (McKinney 2008). *Habitat Provision* is therefore selected as the ES supporting biodiversity and indirectly, the other ES listed in this section.

3.3.3.5 Contribution to physical and mental well-being

Many epidemiological studies have demonstrated various positive health effects of urban natural spaces, including reduced depression and improved mental health, reduced cardiovascular morbidity and mortality, improved pregnancy outcomes and reduced rates of obesity and diabetes (WHO Regional Office for Europe 2016).

However, the pathways leading to beneficial health effects of natural space are diverse and complex (Braubach et al. 2017*a*). In addition to the effects covered by previously discussed ES (air purification, noise attenuation and temperature regulation), existing literature has identified enhanced physical activity, stress compensation, greater social cohesion and engagement with nature as possible pathways for contributing to well-being (Hartig et al. 2014, Lachowycz & Jones 2013, Villanueva et al. 2015).

→ Enhanced physical activity
By providing space for exercise, greenspaces are strongly linked to a better physical health in large conurbations (Davies et al. 2011). Indeed, living in close proximity to greenspace has been shown to promote physical exercise (Bird 2004). There are strong links between the availability of greenspace and greater levels of physical activity and its associated health benefits (TCPA 2018). A study carried out across Europe found that people living in areas with large amounts of greenspace were three times as likely to be physically active as people living in areas where there is little greenspace (Ellaway et al. 2005). Good quality open spaces encourage people to make short journeys on

foot or by bike, and the availability of sport facilities let people engage in physical exercise. Furthermore, children with access to safe, green areas are more likely to be physically active and less likely to be overweight (Davies et al. 2011).

Considering the multiple pathways for natural spaces to contribute to physical activity and the difficulty in quantifying them, an overarching service was defined, *Contribution to physical activity*.

→ Enhanced mental well-being through stress compensation, greater social cohesion and engagement with nature

Urban greenspaces provide a platform for interaction between individuals and groups and thus can promote social cohesion, shared interests and neighbourhood participation and reduce social isolation (Elmqvist et al. 2013). Indeed, urban ecosystems have been found to play a role in enhancing a sense of community. For instance, a study carried out in the Netherlands found an association between the quantity and the quality of streetscape greenery and perceived neighbourhood-scale social cohesion. Research has also shown that community open space and natural settings can promote social integration within disadvantaged communities (Davies et al. 2011).

Furthermore, engagement with nature improves the mental health of city dwellers by enriching their lives with meanings and emotions (Elmqvist et al. 2013). Urban ecosystems play an important role as providers of scenic beauty and opportunities to watch plants and animals – they are the only places where city dwellers can experience nature. Experiencing nature in an urban environment, by visiting parks for instance, has been shown to promote a better mood and improve attention. Benefits to cognitive restoration and self-discipline have also been recorded; these restorative benefits are thought to stem from nature's ability to promote temporary escape and connectedness (Davies et al. 2011). Contact with nature is also linked to healthy childhood development and has been shown to promotes attention restoration, memory, competence, supportive social groups, self-discipline, stress moderation and improvement of behaviour and symptoms of attention deficit hyperactivity disorder (McCormick 2017).

Because of the complex interactions among these pathways, there is little knowledge about how they individually contribute to a lower mental distress and a general better quality of life (Braubach et al. 2017*a*, Houlden et al. 2018). Quantifying the relationship between greenspace and social cohesion or engagement with nature in this project would then rely on limited, mainly qualitative, evidence. However, research on the link between greenspace and the overall alleviation of mental distress has led to robust modelling of the association between indicators of urban greenspace and mental health descriptors (White et al. 2013, Sarkar et al. 2018). Therefore, a relevant service to consider here would be the overall impact of greenspace to mental health, called here *Contribution to Mental Health*.

→ Enhanced mental well-being through urban food growing

UK cities have seen an increase in demand for allotments and community gardens, a sign that urban food growing has intensified recently (Church et al. 2015). For instance, the number of community gardens registered by the Federation of Urban Farms and Community Gardens rose by 65% from 2010 to 2011, while in Edinburgh, the waiting list for an allotment has quadrupled between 1996 and 2016 (Church et al. 2015, City of Edinburgh Council 2016).

However, in-depth knowledge about the benefits of food growing in the UK and other developed countries in still lacking (Caputo 2012). Part of the issue is the complex profiles of food growers and the variety of motivations to undertake food growing. In the UK, food growing has been associated with recreational use by older middle-class households (Church et al. 2015, Davies et al. 2011), while recognising its role in addressing food poverty in communities where growers contribute their produce to their wider social network (Miller 2015). The well-being impacts of growing your own food are therefore variable: although general benefits can be outlined, their relative importance are less clear and likely to vary depending on context. Urban farming allows access of affordable fresh and healthy produce, which has the potential to reduce health inequalities (City of Edinburgh Council 2016, Miller 2015) – nevertheless, food production is not always the primary benefit and food growing is also an opportunity to learn new skills, exercise, relax and socialise (Ackerman 2012, Sustain 2014).

Food growing can therefore be considered as an ES which contributes to health and well-being through many pathways, including, but not restricted to, food production. Food growing also supports the provision of the two previously mentioned services ("contribution to mental well-being" and "contribution to physical activity"). The inclusion of this service acknowledges the increasing importance of space dedicated to urban agriculture.

3.3.4 Scales of provision and scales of benefits

The previous section has highlighted the different ecosystem components known to contribute to the provision of the selected ES. Following the terminology of Burkhard et al. (2014), the set of components required to deliver a given ES is called here a service providing unit (SPU): the SPUs of the breadth of ES considered here are of different scales:

- Site, e.g. small patches of grass, individual trees or allotment beds. ES with site-level SPUs do not require large or diverse greenspaces and can be provided, at least to a certain extent, by a small amount of unsealed area. They include Air purification, Carbon Storage, Run-off Retention, Habitat Provision, Food Growing and Contribution to mental well-being.

- Local, e.g. a public park, a golf course, a community garden or an urban forest. ES with local-level SPUs include those requiring greenspace of a certain size or with some land cover diversity to be provided: Noise attenuation, Temperature regulation, and Contribution to physical activity. Of course, ES with site-level SPUs are also provided at the local-SPU scale.

Benefits derived from ES can occur at different locations and scales (Fisher et al. 2009, Reyers et al. 2013). Here, three scales of so-called "service benefiting areas" (SBA) (Burkhard et al. 2014) can be delineated:

- Local, i.e. neighbourhood or data zone: at this scale, well-being and sustainability benefits can be obtained from all ES – except for carbon storage.
- City / Region: at this scale, well-being and sustainability benefits can be obtained from the run-off retention and habitat provision services. Indeed, locally avoided run-off can benefit the wider catchment and local habitat provided to species can contribute to a wider regional network.
- Global: Avoided carbon emissions at the local scale benefits people at the global scale. A similar observation is made by Raudsepp-Hearne & Peterson (2016) in their study of how observation, management, and analysis of ES shift with scale.

This analysis of the selected ES is synthesised in Figure 3.3 below, adapted from Raudsepp-Hearne & Peterson (2016) to suit the specific context and scope of this study. Figure 3.3 shows the local nature of the benefits derived from the selected ES.

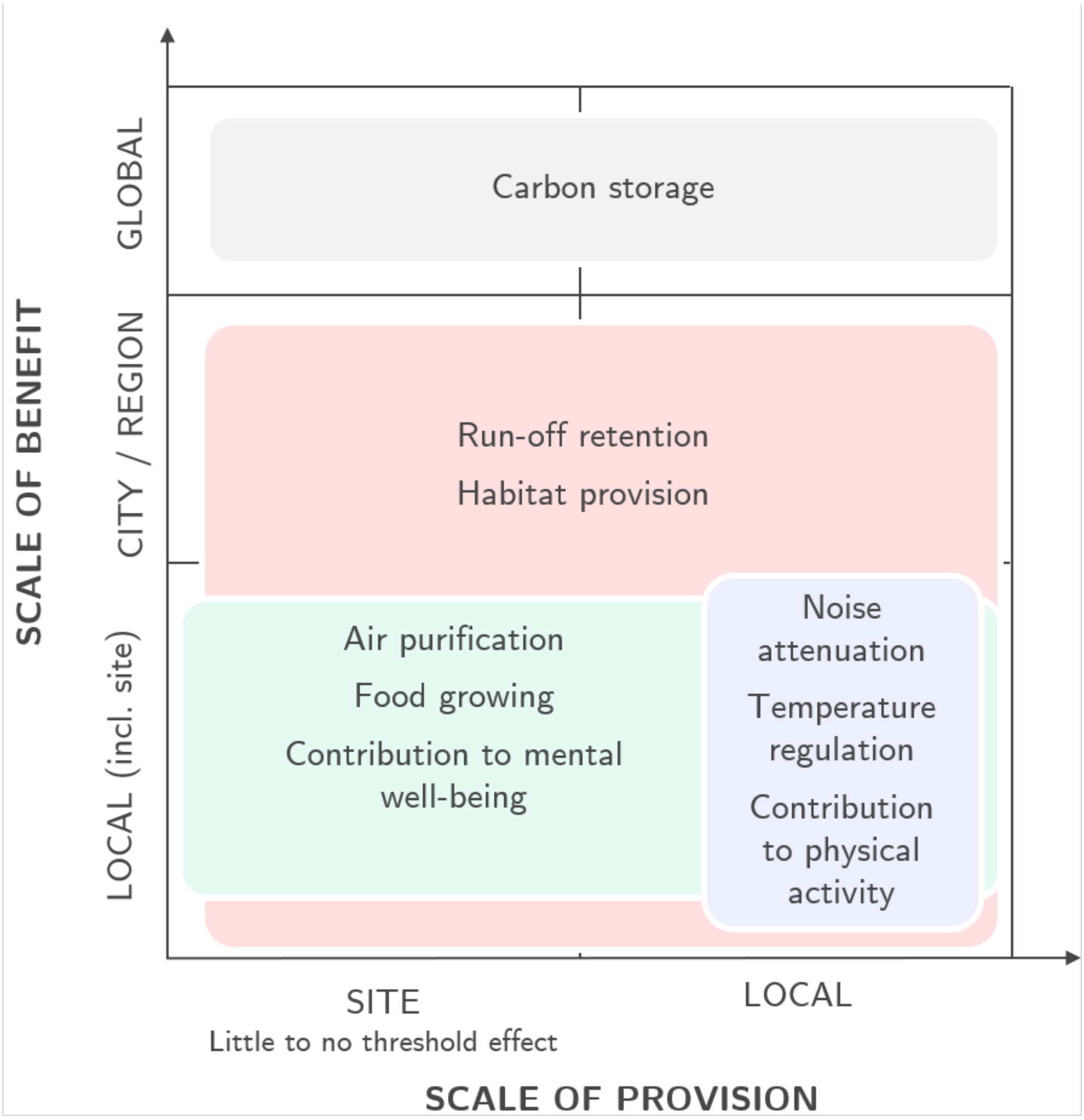


Figure 3.3: Comparing scales of ES provision and benefit distribution.

3.4 Quantification of the individual ecosystem services

3.4.1 Collection of relevant spatial datasets

The main spatial factors likely to influence the provision of the selected ES are the following:

- *Greenspace Structure*: The land cover of natural spaces, i.e. the type of vegetation or water features. Land cover underpins most biophysical processes leading to the material and regulating ES.
- *Greenspace Use*: The function of greenspaces, such as parks or playing fields, which plays a major role in moderating the provision of non-material services (in the context of this study, contribution to physical activity and to mental well-being). Greenspace management for these specific functions is also influencing the extent to which ES are provided.

Nevertheless, section 3.3.3 also hints to the importance of other types of spatial data:

- Road data for the air purification and noise attenuation services, since their provision is influenced by the presence of traffic;
- Soil data for the run-off retention service, which provision depends partly on the capacity of soil to retain water;
- Habitat data for the habitat provision service.

Sources of data for these broad types of spatial information were identified through an online desk search and communication with the City of Edinburgh. It led to the identification of the following data sources, which are all publicly available and accessible (Table 3.2):

Table 3.2: Map products collected

Data source	Map Product
Ordnance Survey (Ordnance Survey 2019)	OS MasterMap Topography Layer: Area, Scale 1:1250
	OS MasterMap Topography Layer: Point , Scale 1:1250
	OS MasterMap Greenspace Layer, Scale 1:2500
	OS MasterMap Highways Network, Scale 1:2500
James Hutton Institute (James Hutton Institute 2018)	Map of soil runoff risk (partial cover), Scale 1:25000
Central Scotland Green Network (Scottish Natural Heritage 2013*b*)	Integrated Habitat Networks, [no scale provided]

A more detailed, nested, classification of spatial data was built from these sources and from the level of information needed to reflect the way the ES are provided, in line with the descriptions in section 3.3.3. The resulting classification defines Categories, Classes and Features as presented in Table 3.3. The definition of each feature is provided in Table 3.4, while the corresponding attributes in collected data sources are reported in Appendix B.

Table 3.3: Types of spatial data relevant for the project

Category	Class	Feature
Greenspace Structure	Vegetation	Trees
		Scrub
		Grass (Rough)
		Grass (Mowed)
	Water	Rivers & Canals
		Ponds & Reservoirs
	Agriculture	Agricultural Fields
		Urban Growing Spaces
	Other	Other unsealed
Greenspace Use	Private Greenspace (or Greenspace with restricted access)	Private Gardens
		Institutional Grounds
	Public Greenspace	Parks
		Cemeteries
		Sport Grounds
		Playing Spaces
Other	Roads	Major Roads
	Soil	Soil compaction
	Habitat network	Habitat network

Table 3.4: Definition of the detailed spatial data relevant for the project

Greenspace feature	Definition
Trees	Areas covered by trees (any type). Includes positioned trees.
Scrub	Vegetation community dominated by shrubs or bushes.
Grass (Rough)	Either rough or un-mowed grassland.
Grass (Mowed)	Managed grassland such as flower beds, mowed lawns, etc.
Rivers & Canals	Water features identified as rivers, canals, or any water body which can be considered as flowing water.
Ponds & Reservoirs	Water features identified as ponds, reservoirs, or any water body which can be considered as static water.
Agricultural Fields[a]	Areas of land with a main purpose of growing crops or keeping livestock.
Urban Growing Spaces[a]	Areas of land for growing fruit, vegetables, and other plants, either in individual allotments or as a community activity.

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Greenspace feature	Definition
Other unsealed	Land which is not covered by vegetation nor water, but which is not sealed either. Includes soil and gravel.
Private Gardens[a]	Greenspace associated with private residences and reserved for private use.
Institutional Grounds[a]	Greenspace normally enclosed and associated with institutions such as universities, schools, hospitals or places of worship. May be reserved for private use or have restricted access.
Parks[a]	Greenspace designed, constructed, managed and maintained as a public park or garden.
Cemeteries[a]	Greenspace associated with burial areas.
Sport Grounds[a]	Greenspace dedicated to the pratice of sports such as golf courses, bowling greens or tennis courts
Playing Spaces[a]	A specially prepared area intended for children's play, usually linked to housing areas or parks and containing purpose built equipment.
Major roads	Main axes of car traffic.

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Greenspace feature	Definition
Soil compaction	Capacity of soil to retain water, based on its topsoil texture (e.g. sandy loam, clay loam) and its draining properties (how well water flows through it).
Habitat network	A habitat network contains habitat and connecting non-habitat land – i.e. land that is permeable to species movement.

[a] Definitions adapted from Ordnance Survey (2017*a*,*b*).

The final type of spatial data required for the assessment relates to the delineation of the study area and its data zones. Data was collected from the UK Data Service (Figure 3.5):

Table 3.5: Spatial boundary data

Data source	Map Product
The Scottish Government (2011)	Data Zone Boundaries 2011
National Records of Scotland (2001)	Scottish Council Areas 2001

Specific note on Private Gardens

The OS MasterMap Topography Layer does not provide data on the Vegetation composition of Private Gardens, which are coded under the Descriptive Group 'Multi Surface'. In order to include the contribution of private gardens vegetation in the assessment, an average typical composition had to be determined. Two UK studies determining the typical composition of gardens were found through a desk research; one located in London (Smith et al. 2011) and the other in Sheffield (Tratalos et al. 2007):

- Tratalos et al. (2007) reported the total percentage of land cover estimated from a sample of 70 randomly selected gardens in three different study sites (Table 3.7). Their land cover types were matched with the ones used in this study with the following assumptions:
  - ‘Turf grass and flowerbed’ was assigned to ‘Grass (mowed);
  - ‘Rough grassland’ was assigned to ‘Grass (rough);
  - ’Earth or gravel’ was assigned to ’Other unsealed’.
- Smith et al. (2011) reported the total percentage of land cover categories for the 37,900 ha total garden space of London in 2006-2008 (Table 3.6). Their land cover types were matched with the ones used in this study with the following assumptions:
  - The percentage of ‘Mixed vegetation’ was assigned to ‘Scrub’ and ’Grass (rough)’ according to the proportions found in Sheffield ;
  - The percentage of sealed and permeable surface contained in ‘Hard surfaces’ was assigned to ‘Sealed’ and ‘Other unsealed’ according to the proportions found in Sheffield;
  - The category ’Other land cover’ was considered as if being sealed (conservative assumption).

The typical composition used in this project is the mean of the percentage of land cover derived from the two aforementioned studies (Table 3.8).

Table 3.6: Total percentage of land cover categories for the 37,900 ha total garden space of London in 2006-2008 (Smith et al. 2011)

Land cover	Definition	Percentage
Lawn	A grass/turf area. May be densely or sparsely vegetated, tall or closely mowed.	29%
Tree canopy	A tree refers to a mature woody species (or with a 2m wide canopy).	18%
Mixed vegetation	Includes small to medium sized (<2m wide) herbaceous or woody plants - flowers, shrubs etc. such as grown typically in a flower bed - scrub growth such as bramble cover, climbers such as ivy or wisteria and hedges.	10%
Hard surfaces	Includes paving, bricks, concrete, gravel, patios, paths, steps and driveways.	33%
Garden buildings	All sheds, glasshouses, summerhouses and other small (<12m^2) detached buildings	7%
Side passages	Narrow side path or passage along the side or between houses that is included within the garden polygon. Likely to be hard surface.	2%
Other land cover	Either unknown or not fitting in the previous categories (e.g. pools or garden debris)	1%

Table 3.7: Total percentage of garden land cover estimated from a sample of 70 randomly selected gardens in three different study sites in Sheffield (Tratalos et al. 2007)

Land cover	Definition	Percentage
Turf grass and flower beds	Also referred to as 'grass' in the article. Describes natural vegetation which is not classified as woodland, scrub or rough grassland, and which lacks tree cover.	37%
Rough grassland	No definition provided, assumed to refer to the commonly accepted definition of rough grassland in the UK	10%
Scrub	No definition provided, assumed to refer to the commonly accepted definition of scrub	12%
Earth or gravel	No definition provided, considered to refer to permeable non-vegetated areas.	8%
Sealed	Sealed surfaces	33%

Table 3.8: Typical vegetation composition of the Private Garden greenspace Feature

Vegetation Feature	Percentage
Trees[a]	9%
Grass (mowed)	33%
Grass (rough)	7.3%
Scrub	8.7%
Other unsealed	7.2%
Sealed	34.8%

[a] Considered at 0% for Sheffield gardens.

The typical composition estimates the proportion of vegetation at 58%. This figure is consistent with the results from a study published in 2019 by the Data Science

Campus of the UK Office for National Statistics (ONS), which estimated that around 62% of garden space in Great Britain is vegetated (Bonham et al. 2019).

Specific note on Individual Trees

Individual Trees are point features representing trees otherwise not accounted in Trees areas. For them to be taken into account in the services values at data zone scale, it was necessary to assign to them a crown area.

Vaz Monteiro et al. (2016) measured the crown width of a sample of trees of small and large statures in Edinburgh, as part of a study on allometric relationships for urban trees in Great Britain. The mean across all species investigated is around 6m, giving an approximate crown radius of 3m and an estimate crown area of $27m^2$. This is consistent with the value obtained by Derkzen et al. (2015) in their assessment in Rotterdam.

3.4.2 Determining the relationships between spatial data and the selected ecosystem services

3.4.2.1 Specific methodology for developing models

The relationships between greenspace spatial data and the selected ES are modelled using results from existing empirical studies. Three methodological points are addressed in this section:

- The selection of relevant ES indicators;
- The identification of relevant empirical studies;
- The assessment of uncertainties.

Aspect 1: Selection of relevant indicators

A large number of indicators have been used to assess urban ES, with differing quality and applicability (Haase et al. 2014) The identification of suitable indicators relied on criteria aiming at ensuring, as much as possible, their salience, credibility and legitimacy. For each ES:

1. *The indicator uses a metric reflecting the service's relationship with spatial parameters.*

   For instance, if research shows that the relationship between a service and land area is not linear, then having an indicator measured per unit of area is not adequate. The adequacy of potential metrics may not be obvious *a priori*, therefore assessing this criterion was conducted while developing the models, in an iterative manner.

2. *The indicator is simple to understand, but has a level of complexity that means it is sensitive to the main influencing factors*

   For instance, if research has shown that vegetation land cover is not enough to explain the largest variations in the provision of a service, then the indicator should not be based on vegetation land cover alone. As above, assessing this criterion was conducted while developing the models, in an iterative manner.

3. *Credible and legitimate data is available to support its assessment.*

   A hierarchy of data sources was established based on their credibility and legitimacy (Figure 3.4). This hierarchy effectively established different levels of priority for the inclusion of data sources in the assessment. As a result, when two indicators both comply with the criteria 1 and 2 above, the one assessed with data from studies having a higher 'level of priority' is preferred.

4. *The indicator limits the introduction of uncertainties.*

   Relying on a minimal amount of input data, as chosen in this project, has the clear advantage of a gain in simplicity and time - but has the important drawback of increasing uncertainties. Depending on the service assessed, the impact on the magnitude of uncertainties can be quite large. If an indicator of relevance cannot be directly derived from greenspace data using existing studies, and must instead be assessed by using two or more models back to back, the amount of uncertainties is likely be too large to have confidence in the resulting value. To avoid this risk, only metrics directly derived from greenspace data are used in the project.

The description of each model in the following sections provides a short rationale for choosing the indicators, based on the criteria above.

Aspect 2: Identification of relevant empirical studies

A desk search on Google and Google Scholar and Scopus was conducted to collect peer-reviewed academic publications reporting results of empirical studies. A search on Google was also conducted to review the grey literature. To ensure the quality of data collected and its applicability to the context of the project, a hierarchy of data sources was developed (Figure 3.4). It sets four levels of priority regarding which data sources ought to be considered:

- The preferred data sources are peer-reviewed studies commissioned by the studied city or by other UK governmental bodies as well as chartered institutes (respectively levels 1a and 1b). This type of 'official' sources bring credibility to the assessment because they come from recognised institutions, and at the same time have a high applicability as they stem from local assessments (level 1a) or at least from the UK.

- When commissioned studies were not available, peer-reviewed literature was considered. Publications reporting UK data were preferred (level 2), then international studies (level 3). Confidence in data quality in both these cases comes from the peer-review process; however, results from international studies are expected to have a lower applicability that those originating from sources matching level 1 and 2, mainly for climate- and culture-related reasons.

- In the absence of any empirical studies providing quality data, relevant spatial data is used as a proxy for the ES (level 4). For instance, lack of data about crop yields may lead to using the area of agricultural fields instead.

The reliability of data sources, qualitatively assessed with the levels above, is reported for each service in the sections detailing the models developed for their valuation.

Figure 3.4: Hierarchy for the selection of data sources

Aspect 3: Assessment of uncertainties

A qualitative description of limitations is provided for each service, and when possible, a quantitative assessment of uncertainties was conducted. The assessment involved defining two scenarios, 'Low' and 'High', from values reported in the collected studies. If standard errors were reported, then the Low scenario corresponded to the lower boundary and the high scenario to the upper boundary. If not, then the Low scenario corresponded to the minimum value reported and the high scenario to the maximum.

3.4.2.2 Models of the relationships between spatial data and the selected ecosystem services

The key features of the developed models are presented in the next pages. The detailed rationale for establishing these features is available in Annex.

Model for Air Purification

Indicator	Capture rate of PM_{10} ($g.m^{-2}.yr^{-1}$)
Spatial data used	Trees, Grass (both types), Scrub, Private Gardens, Major Roads
Short description	Estimating the average removal of particles by vegetation in each data zone. Each relevant Greenspace Feature is assigned a capture rate, which is increased by a factor of 2 around major roads. A weighted average using the areas of Features in each data zone is then calculated.
Model	*Step 1:*

Greenspace Feature	Output if not in a 50m-buffer around major roads ($g.m^{-2}.yr^{-1}$)	Output if in a 50m-buffer around major roads ($g.m^{-2}.yr^{-1}$)
Trees	4.41 (3.97, 4.85)	8.82 (7.94, 9.70)
Grass	0.02 (0, 0.9)	0.04 (0, 1.8)
Scrub	2.64 (1.08, 4.11)	5.28 (2.16, 8.22)
Private Gardens	0.69 (0.48, 0.9)	1.38 (0.96, 1.8)

Step 2: Weighted average across the data zone

Sources	Jones et al. (2017), Baumgardner et al. (2012), Escobedo & Nowak (2009), Derkzen et al. (2015)

Model for Noise Attenuation

Indicator	Noise reduction (dBA)
Spatial data used	Trees, Major Roads
Short description	Patches of trees, especially around main roads reduce the noise generated by traffic and other noise-producing activities. The amount of reduction depends on several parameters (width of patch, density and size of trees, etc.) A first approximation is to only consider contiguous patches of non-scattered trees with an area higher than 200 m^2, and assigning them a decibel attenuation based on their size and their closeness to roads. The expected value of noise reduction inside a datazone, based on area covered by relevant tree patches, is then calculated.
Model	*Step 1:*

Greenspace Feature	Condition	Output (dBA)
Trees not intersecting a 50m-buffer around major roads	$200m^2 \leq Area < 3,000m^2$	1
	$Area \geq 3,000m^2$	2
Trees intersecting a 50m-buffer around major roads	$200m^2 \leq Area < 3,000m^2$	2
	$Area \geq 3,000m^2$	4

Step 2: Expected value across the data zone

Sources eftec (2018*b*), Derkzen et al. (2015)

Model for Carbon Storage

Indicator	Density of above-ground carbon stored ($kgC.m^{-2}$)
Spatial data used	Trees, Grass (both types), Scrub, Private Gardens
Short description	Estimating the average density of carbon stored in each data zone. Each relevant Greenspace Feature is assigned a density. A weighted average using the areas of Features in each data zone is then calculated.
Model	*Step 1:*

Greenspace Feature	Output ($kgC.m^{-2}$)
Trees	9.19 (5.67, 12.72)
Scrub	2.27 (1.92, 2.61)
Grass	0.14 (0.13, 0.15)
Private Gardens	1.08 (0.76, 1.40)

Step 2: Weighted average across the data zone

Sources	Davies et al. (2011), Doick et al. (2017), Larondelle & Haase (2013), Strohbach & Haase (2012)

Model for Temperature Regulation

Indicator	Temperature reduction (°C)
Spatial data used	Trees, Grass (both types), Scrub, Private Gardens (contiguous), Rivers / Canals, Ponds / Reservoirs
Short description	Estimating the average temperature reduction one can experience in each data zone. Each relevant Greenspace Feature is assigned a typical cooling property based on its size. The largest features are also assigned a buffer in which their cooling persists. The expected value of temperature reduction is then calculated.
Model	*Step 1:*

Greenspace Feature	Condition	Output
Trees	$Area \geq 3ha$	100m-buffer
Rivers / Canals	$Width \geq 25m$	30m-buffer
Ponds / Reservoirs	$Area \geq 700m^2$	30m-buffer

Step 2:

Greenspace Feature	Condition	Output (°C)
Trees	$Area \geq 200m^2$	-3.5
Buffer around trees	-	-0.52
Rivers / Canals	$Width \geq 25m$	-1.4
Buffer around rivers / canals	-	0.8
Ponds / Reservoirs	$Area \geq 700m^2$	-0.1
Buffer around ponds / reservoirs	-	-0.057
Grass or Scrub	$Area \geq 200m^2$	-0.95
Private Gardens	$Area \geq 200m^2$	-0.95

Step 2: Expected value across the data zone

Sources eftec (2018*a*)

Model for Run-off Retention

Indicator	Run-off retention rate ($L.m^{-2}$)
Spatial data used	Trees, Grass (rough), Grass (mowed), Scrub, Private Gardens, Agricultural Fields
Short description	Estimating the average reduction of water run-off volume per square meter in each data zone. Each relevant Greenspace Feature is assigned a retention rate value. A weighted average using the areas of Features in each data zone is then calculated.
Model	*Step 1:*

Greenspace Feature	Output ($L.m^{-2}$)
Trees	9.85 (5.92, 12.00)
Scrub	8.08 (4.57, 11.09)
Grass (mowed)	8.93 (5.26, 11.62)
Grass (rough)	9.41 (5.70, 12.00)
Private Gardens	6.45 (3.89, 8.94)
Agricultural Fields	9.04 (8.60, 9.41) if low soil compaction 8.05 (6.34, 8.60) if moderate soil compaction 6.55 (4.33, 9.10) if high soil compaction

Step 2: Weighted average across the data zone

Sources	Tratalos et al. (2007), Whitford et al. (2001), USDA-NRCS (2009, 2004), Lilly & Baggaley (2014)

Model for Habitat Provision

Indicator	Habitat score (0 - 5 range)
Spatial data used	Central Scotland Green Network Integrated Habitat Network (CSGN IHN) Data
Short description	The CSGN IHN contains habitat and connecting non-habitat land of five types: broadleaved woodland, wetland (fen marsh swamp only), neutral grassland, acid grassland and heathland. Considering SNH guidance that a network (or part of) which overlays another network(s) has a greater ecosystem function and has a higher importance, the modelling occurs in two steps: first, pieces of network are given a score of 1 to 5 depending on whether they overlapped 0, 1, 2, 3 or 4 other networks, respectively. Then, a weighted average of the network areas, modulated by their scores, gives the importance of the data zone for habitat provision, measured on a scale of 1 to 5.
Model	*Step 1:* Scoring pieces of habitat network based on overlap with other networks

Number of overlaps	Score
0	1
1	2
2	3
3	4
4	5

Step 2: Weighted average across the data zone

Sources	Scottish Natural Heritage (2013*b*,*a*)

Model for Food Growing

Indicator	Proportion of land dedicated to food production (no unit)
Spatial data used	Agricultural Fields, Urban Growing Spaces
Short description	In the absence of data about yields, land cover is used as proxy.
Model	Food production is estimated by calculating the proportion of Agricultural Fields and Urban Growing Spaces.
Sources	-

Model for Mental Health

Indicator	Decrease in mental distress (General Health Questionnaire score, range 0-3)
Spatial data used	Vegetation, Water, Private Gardens
Short description	A longitudinal study has linked lower mental distress and higher life satisfaction to the amount of greenspace in the participants' neighbourhood (controlling for other variables). The study shows that 1% increase in greenspace density leads to a decrease of 0.0043 in the General Health Questionnaire mental distress scale (0-3 range). The contribution of a specific data zone is assessed by multiplying the proportion of all types of green areas by 0.43.
Model	Proportion (Vegetation, Water, Private Gardens) * 0.43 (0.30, 0.56)
Sources	White et al. (2013), Braubach et al. (2017*b*)

Model for Contribution to Physical Activity

Indicator	Increase in QALY (QALY per capita per year)
Spatial data used	Public Greenspace
Short description	The average number of visits to a local greenspace for physical exercise meeting health guidelines, per capita and per year in urban Scotland, depending on whether one lives within 5, 10 or more minutes from it, was derived from sources from SNH and Greenspace Scotland. This value was multiplied by the approximate increase in QALY per capita per year associated with moderate to intense exercise, to give an estimate of the increase in QALY due to visits to local greenspaces, depending on their walking time from home (5min, 10min or more). Time was converted into buffer distance by adjusting a first approximation of 5min <-> 400m with household survey data, which gave of 5min <-> 250m. The contribution of a specific data zone to physical activity is then estimated by computing the weighted average of area falling with 5 or 10 min walking time, modulated by the corresponding increase in QALY. The size of the greenspace was not taken into account.
Model	*Step 1*:Assigning approximate increases in QALY per capita

Greenspace Feature	Output (QALY per capita per year)
Public Greenspace	0.00495 (0.0487, 0.00503)
264m-Buffer around Public Greenspace	0.00495 (0.0487, 0.00503)
264 to 412m-Buffer around Public Greenspace	0.00325 (0.00319, 0.0033)

Step 2: Weighted average across the datazones

Sources	Greenspace Scotland (2018), Wilson, V. & Seddon (2018), White et al. (2016), Environment Agency (2018), *Distance to Green or Blue Space - Scottish Household Survey* (n.d.)

3.4.3 Spatial distribution of the individual ecosystem services

Maps of the nine ES were generated using ArcGIS® software by Esri (ArcGIS Pro, version 1.4). The models described in section 3.4.2 are coded in Python 3.5.4 using ArcPy (Python Software Foundation 2017).

The distribution of ES values across the data zones are visualised using violin plots (Figure 3.5) in addition to the nine individual maps (Appendix D.1). Figure 3.5 plots the distribution density of the services along with their median and mean absolute deviation around the median (MAD). The distributions are consistent with the expected structure of the dataset introduced in section 2.3.2:

- Skewness:

  For all services but Run-off Retention, Contribution to Mental Health and Contribution to Physical Health, the bulk of the data sits at the bottom of the graph. It indicates that values in most data zones are lower than the mean, with a limited number of data zones having higher values (the tail of the distribution). For Contribution to Physical Health, the bulk of the data sits at the top of the graph - indicating that It indicates that values in most data zones are higher than the mean. Run-off Retention and Contribution to Mental Health have reasonably symmetrical distributions: compared to the other services, they do not feature big differences in provision across the data zones. An analysis of skewness confirms the qualitative interpretation from the plots: all services but Run-off Retention and Contribution to Mental Health significantly deviate from a normal distribution, in terms of skewness (Appendix D.3);

- Zero-inflation:

  Three services, Habitat Provision, Noise Attenuation, and Food Growing, feature a large number of zeroes: the proportion of zeroes in their distribution is 0.035, 0.27 and 0.87 respectively - compared to a maximum of 0.0018 among the other services.

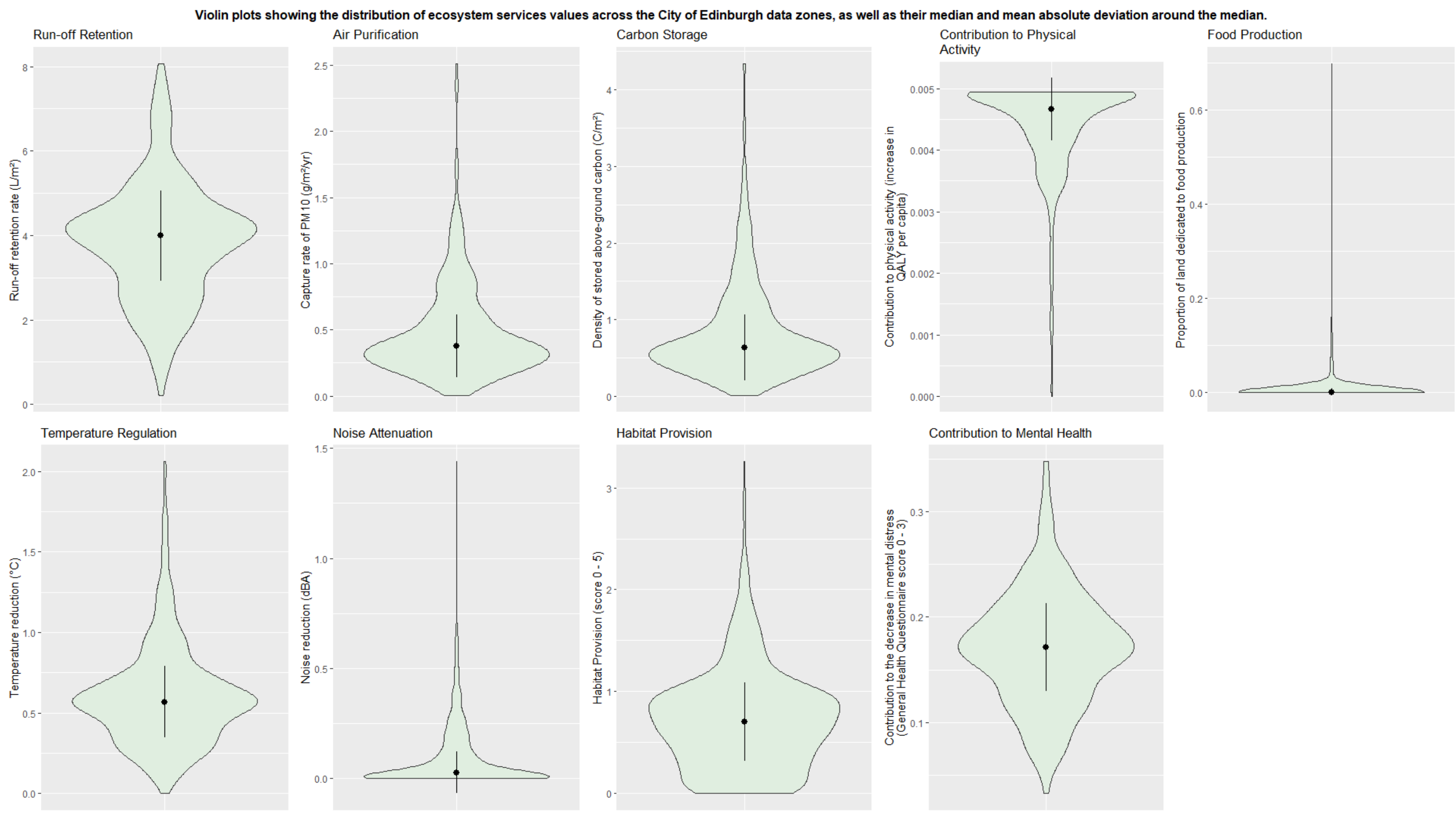

Figure 3.5: Violin plots of the distribution of the nine selected ES across the City of Edinburgh.

Pair-wise scatter plots (Figure 3.6) show clear relationships among some of the services, while the individual maps display similar patterns for some of them. This suggests a possible structure in the dataset, which is identified and analysed in the next sections.

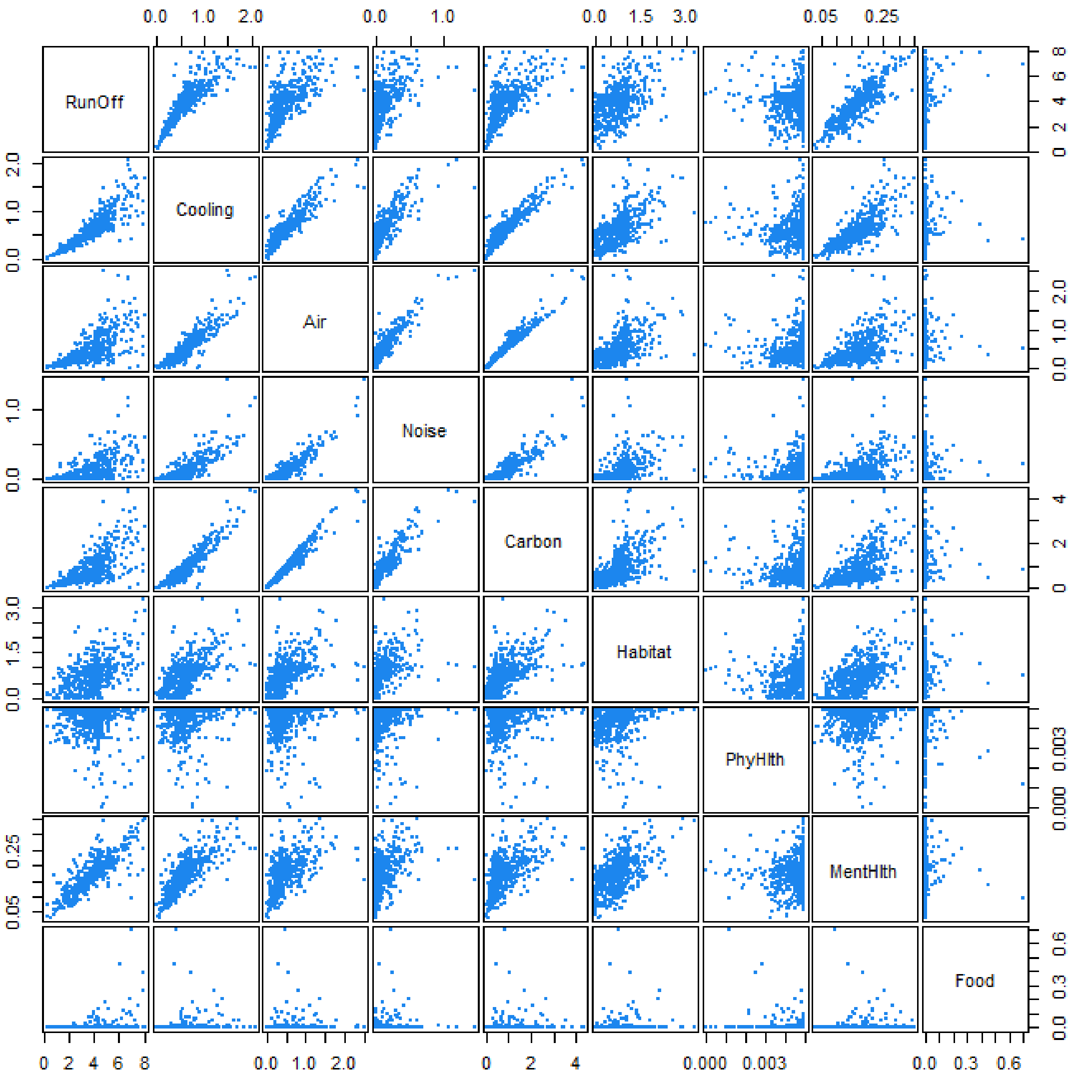

Figure 3.6: Pair-wise scatter plots of the nine selected ES across the City of Edinburgh.

3.5 ES bundles

The methodology described in Chapter 2 is applied to the Edinburgh dataset using R (R Core Team 2019). The Hellinger transformation is conducted with the *decostand* function of the *vegan* package (Oksanen et al. 2019) and the PCA with the *prcomp* function of the core *stats* package. The PCA plot is visualised with the *factoextra* package (Kassambara & Mundt 2017), the dendrogram with the *dendextend* package (Galili 2015) and the correlation matrix with the *ggcorrplot* package (Kassambara 2019).

Figure 3.7 shows the proportion of variance contained in the nine principal components. The first two hold 67% of the dataset variance, while the others have each a small share of the remaining 33%. Therefore, the first two components (PC1 and PC2) are considered enough to represent the data. Figure 3.8 shows that all services but Food Growing played a medium to high role in defining the two PCs, meaning that a large proportion of the variation of all services but Food Growing is represented by PC1 and PC2. The limited role of Food Growing in defining the PCs can be explained by the high proportion of zeroes in its distribution: in a PCA preceded by a Hellinger transformation, such zero-inflated variables can be expected to have a low impact on the definition of PCs (see section 2.4.2).

Figure 3.8 also shows that PC1 discriminates between Contribution to Physical Activity and the other services, while PC2 highlights the differences between the remaining services. The position of Contribution to Physical Activity in the plot can be easily explained by the fact that its spatial occurrence, unlike other services, is not directly linked to natural elements: the extent to which people in a data zone benefit from greenspaces' contribution to physical activity depends on their distance to these greenspaces, which could be located in a different data zone. Therefore, high levels of Contribution to Physical Activity can occur in data zones where vegetation and water is scarce, which is not the case for the other services.

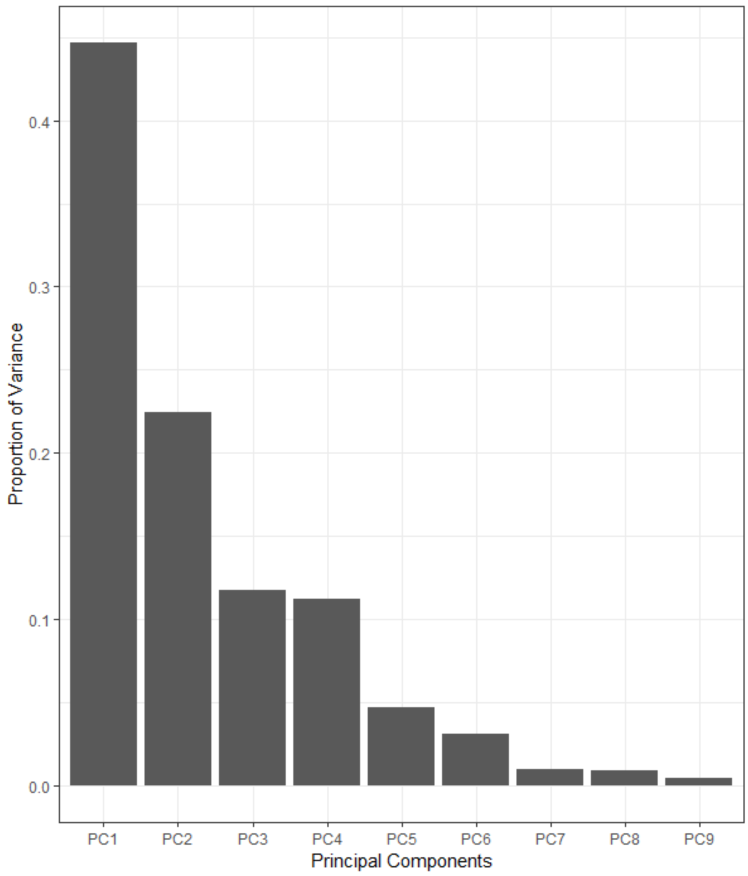

Figure 3.7: Proportion of the dataset variance contained in the nine principal components. The first two components hold most of the variance.

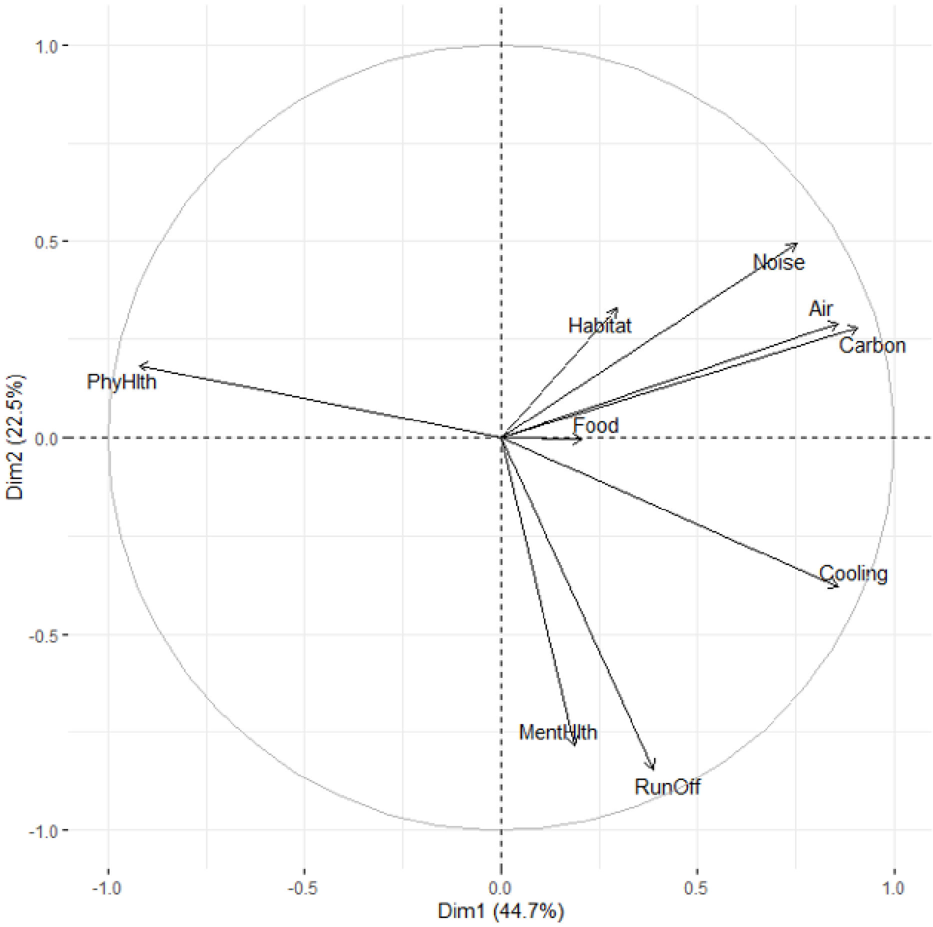

Figure 3.8: Plot of the ES in the two-dimensional space generated by the first two principal components of the tb-PCA.

ES Bundles are identified from the PCA plot using (i) a hierarchical clustering analysis of the dataset projection onto PC1 and PC2, and (ii) pair-wise correlation coefficients (Figure 3.9 below). Three main clusters can be identified from the hierarchical clustering analysis (Appendix D.2):

- Cluster 1: Temperature Regulation, Run-off Retention, Contribution to Mental Health;
- Cluster 2: Habitat Provision, Noise Attenuation, Air Purification, Carbon Storage, Food Growing;
- Cluster 3: Contribution to Physical Health.

The presence of Food Growing in Cluster 2 is challenged by the PCA results and the correlation coefficients. While the other ES in Cluster 2 have a medium to high role in defining the two PCs, Food Growing only contributes in a limited way to the overall variation of the dataset. It also has very low correlations with the other ES (Figure 3.9). These two findings indicate that Food Growing cannot be said to be consistently associated with the other ES in Cluster 2, and call for the assignation of Food Growing to its own bundle.

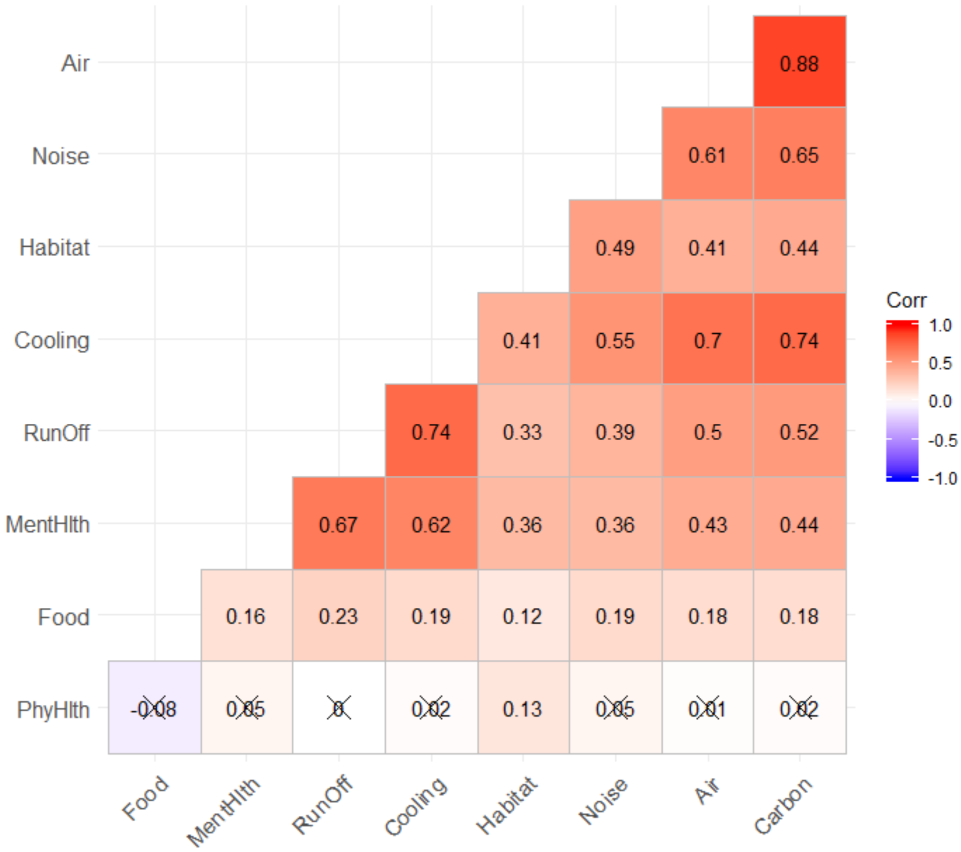

Figure 3.9: Correlation matrix of Kendall τ_b coefficients. Non-significant coefficients are crossed.

Apart from this specific case, the cluster assignations delineated by the hierarchical analysis are those expected from the position of the ES in the PCA plot. First, the analysis identifies two sets of clusters along PC1: cluster 3 on the one hand and Cluster 1 & 2 on the other hand. The assignation of Contribution to Physical Health to its own cluster (Cluster 3) is consistent with its lack of significant correlations to any of the services (except Habitat Provision, for which correlation is low), while all other ES are positively correlated to each other (Figure 3.9).

Along PC2, two clusters are identified: Cluster 1 and Cluster 2. All the ES in Cluster 1 are strongly correlated with each other (coeffs > 0.6), as are Air Purification, Carbon Storage and Noise Attenuation within Cluster 2 (Figure 3.9). In contrast, Habitat Provision has lower pair-wise correlations with the other ES (coeffs from 0.33 to 0.49), although generally higher with those from its own cluster (Cluster 2). Furthermore, both Air Purification and Carbon Storage have high correlation coefficients with Temperature Regulation, although the latter belongs to another cluster. The clustering results for Habitat Provision and Temperature Regulation stress the fact that identifying bundles is not about finding independent groups, but rather optimising the similarity among group members.

In the end, four ES Bundles can be found, as plotted in Figure 3.10:

- Bundle 1: Temperature Regulation, Run-off Retention, Contribution to Mental Health;
- Bundle 2: Habitat Provision, Noise Attenuation, Air Purification, Carbon Storage;
- Bundle 3: Contribution to Physical Health;
- Bundle 4: Food Growing.

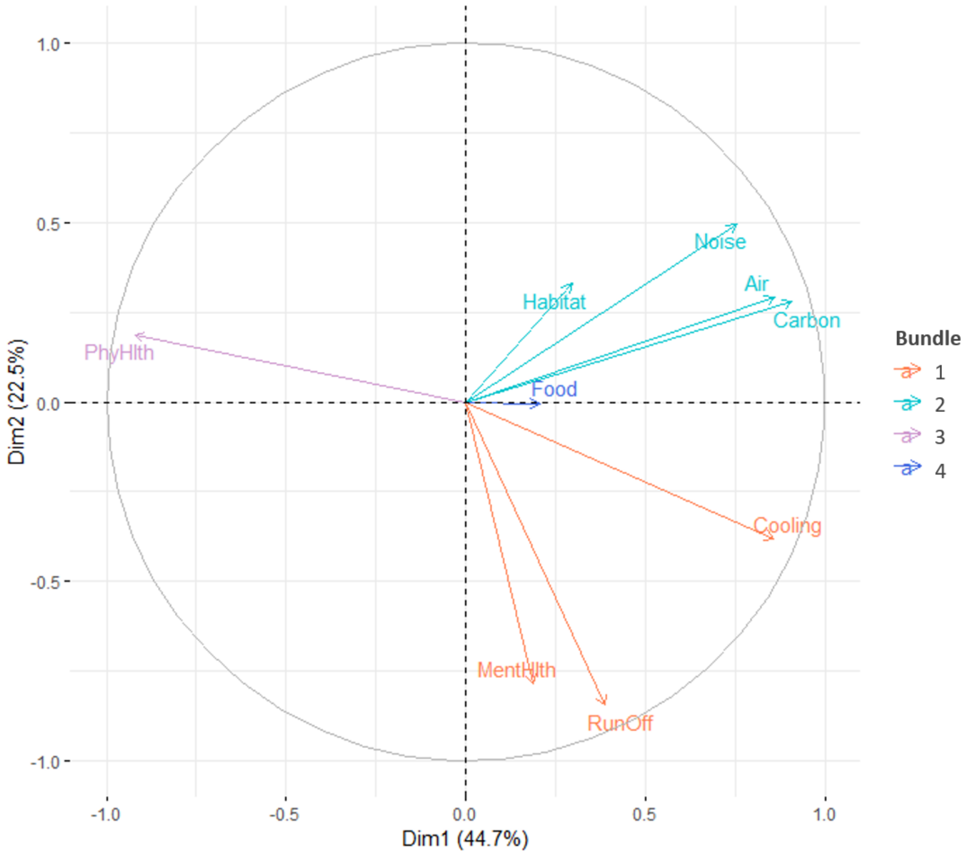

Figure 3.10: The four ES Bundles identified in Edinburgh, plotted in the two-dimensional space generated by the first two principal components of the tb-PCA.

The position of the four bundles in the PCA plot, coupled with the empirical knowledge on the services reviewed in Appendix C, allows to provide a qualitative interpretation of the two PCA axes, i.e. putative explanations for the dataset variations. First, PC1 seems to discriminate ES depending on whether their value in a data zone relies mainly on natural cover inside it (right side of the plot) or both inside and outside (left hand side). As a result, PC1 reflects the extent to which the natural cover of a data zone influences ES provision. PC2 can be qualitatively interpreted using Bundles 1 and 2: it appears that the processes leading the provision of ES in Bundle 2 are mostly performed by trees (e.g. capture of air particles or storage of above-ground carbon), while the importance of trees is not as predominant in the provision of the other services. For instance, differences among different vegetation types are much smaller for their run-off retention rates than they are for their carbon density. Similarly, various types of natural features are able to provide a cooling service when they cover more than a certain area, and mental health benefits are detected in neighbourhoods with different sorts of natural cover. PC2 seems therefore to discriminate between services heavily depending on tree cover (top half of the plot) from those which also rely on other types of land cover (bottom half of the plot).

This qualitative explanation of the patterns of variations is explored quantitatively using regression analyses in section 3.7.

3.6 Spatial bundles

The methodology described in Chapter 2, involving the test of multiple combinations of transformation, standardisation and projection, is applied to the Edinburgh dataset using R (the specific packages used are referenced in the relevant sections). Bundle maps are generated using ArcGIS Pro v1.4.

3.6.1 Data transformation

The Box-Cox transformation applied to the dataset is coded in R using the *boxcox* function of the *EnvStats* package (Millard 2013).

3.6.2 Data standardisation

3.6.2.1 Median z-scores, interdecile and range standardisation

Functions are created in R to generate the standardised datasets. Both transformed and non-transformed datasets were subject to standardisation.

3.6.2.2 Ordinal scoring

The ES with the lowest range of variation is Run-Off Retention, which spans over 7.37 MADs (Table 3.9). The scoring range is therefore set to an 8-point scale, from 1 to 8. Both transformed and non-transformed datasets were subject to standardisation.

Table 3.9: Ecosystem services' ranges of variation relative to the median and measured in mean absolute deviation around the median (MAD) units

Ecosystem service	Range in MAD units
Run-Off Retention	[-3.55, 3.82]
Temperature Regulation	[-2.55, 6.68]
Air Purification	[-1.56, 8.94]
Noise Attenuation	[-0.26, 14.97]
Carbon Storage	[-1.46, 8.63]
Habitat Provision	[-1.84, 6.66]
Contribution to Physical Health	[-9.20, 0.56]
Contribution to Mental Health	[-3.33, 4.24]
Food Production	[0.00, 91.33]

3.6.3 Projection

3.6.3.1 Median z-scores, interdecile and range standardised datasets

MDS is conducted using the *cmdscale* function available in the core *stats* package of R.

3.6.3.2 Ordinal-scored datasets

MCA was conducted using the *MCA* function of the *FactoMineR* package (Lê et al. 2008) and the first two components were retained.

3.6.4 Clustering

The optimal number of clusters for each combination of transformation, standardisation and projection was determined graphically using the *fviz_nbclust* function of the *factoextra* package (Kassambara & Mundt 2017). The Silhouette method was used to identify whether the best bundle solution had an average Silhouette width higher than 0.50 - as explained in Chapter 2, only solutions with a bundle number higher than two were considered. An example is provided in Figure 3.11.

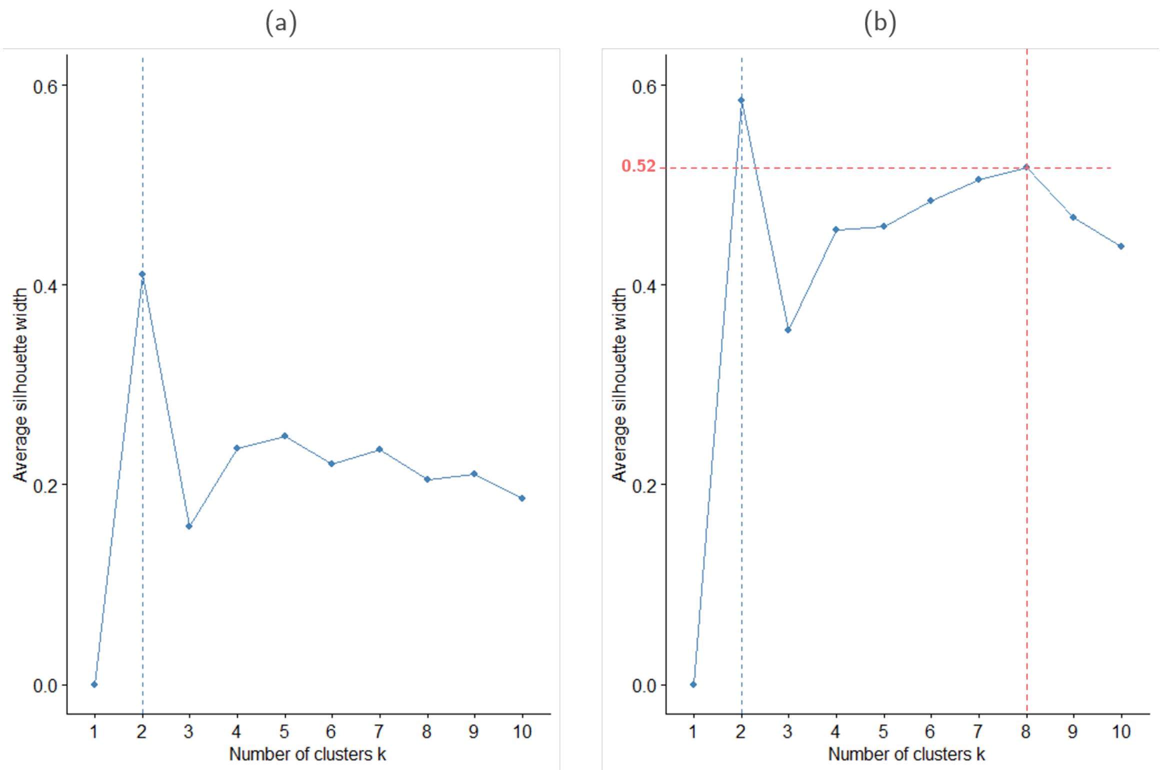

Figure 3.11: Determining the optimum number of clusters using the Silhouette method: (a) shows an example where no optimum is found as no solution has an average Silhouette width higher than 0.50 (NM dataset); (b) shows an example where the optimum number of clusters is 8 (NME dataset). The two-cluster solution is not considered although it has the maximum average Silhouette width.

Datasets with an acceptable bundle solution span across the breadth of tested combinations, with an optimum number of bundles ranging from 3 to 8 (Table 3.10). They are clustered using the *pam* function of the *cluster* package (Maechler et al. 2019) in order to identify their bundle patterns. These patterns are visualised and analysed in the next section.

Table 3.10: Potential bundle solutions and their characteristics

Code name	Dataset characteristics	Number of bundles
NI	Non-transformed, interdecile standardised, non-projected	3
NIE	Non-transformed, interdecile standardised, projected with a conservation of Euclidean distances	3
NIM	Non-transformed, interdecile standardised, projected with a conservation of Manhattan distances	3
YRh	Transformed, range standardised, projected with a conservation of Hellinger distances	3
Ymca	Transformed, standardised with ordinal scores, projected	3
YME	Transformed, standardised with median z-scores, projected with a conservation of Euclidean distances	5
Nmca	Non-transformed, standardised with ordinal scores, projected	5
NME	Non-transformed, standardised with median z-scores, projected with a conservation of Euclidean distances	8

3.6.5 Analysis and visualisation of the possible solutions

The eight solutions identified in previous steps are analysed using heatmaps, violin plots and maps:

- Heatmaps plot the medians of values for each ES and each bundle using a colour gradient. The medians are measured in MAD units: for instance, a value of 0 for a couple {ES, bundle} means the median of values in that bundle is at the same level as the median across the whole city. A positive (resp. negative) value means that the median of values in that bundle is higher (resp. lower) than the median across the whole city. They provide a way to visualise the relative differences among bundles - see example below (Figure 3.12) and throughout this section. Heatmaps are created using the *ggplot2* package (Wickham 2016).

- Violin plots show how ES values are distributed across the different bundles, by plotting the shape of their distribution for each ES and each bundle. They provide additional details to the information conveyed by heatmaps - see example for one service below (Figure 3.12) and throughout this section. Violin plots are created using the *ggplot2* package.

- Maps show the spatial distribution of bundles across the city by assigning a different colour to data zones depending on their bundle.

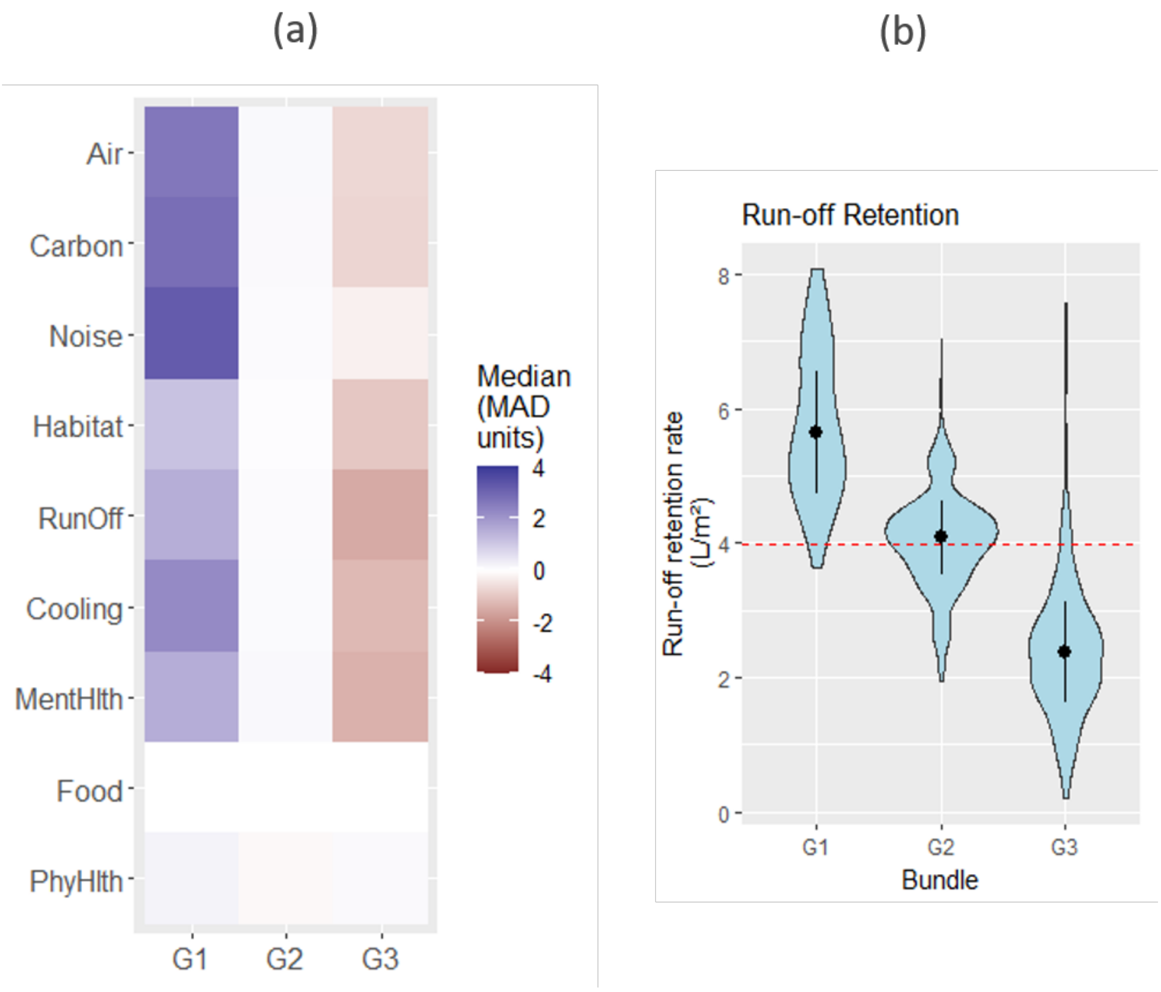

Figure 3.12: Examples of plots generated to describe the bundle solutions. (a) Heatmap for Ymca and (b) Violin plots for the Run-Off Retention service, representing the distribution of values for each Ymca bundle. The red dotted line marks the median across all values.

The next paragraphs describe the patterns evidenced by the identified solutions and provide a rationale for the final selection of the optimal spatial bundles.

3.6.5.1 NI, NIE, NIM

The 3-bundle solutions identified from clustering interdecile-standardised datasets (NI, NIE and NIM) discriminate data zones based solely on their level of Food Growing. They gather in the same bundle all data zones with no or very little Food Growing and assign the two other bundles depending on the proportion of land dedicated to

Food Growing (Figure 3.13). As a result, most data zones – 95% of them for the NI solution – are grouped in the first bundle, a pattern which masks the variation of other services than Food Growing in the area it covers. Such a pattern does not give sufficient information on differences within the city and is therefore discarded (Figure 3.13).

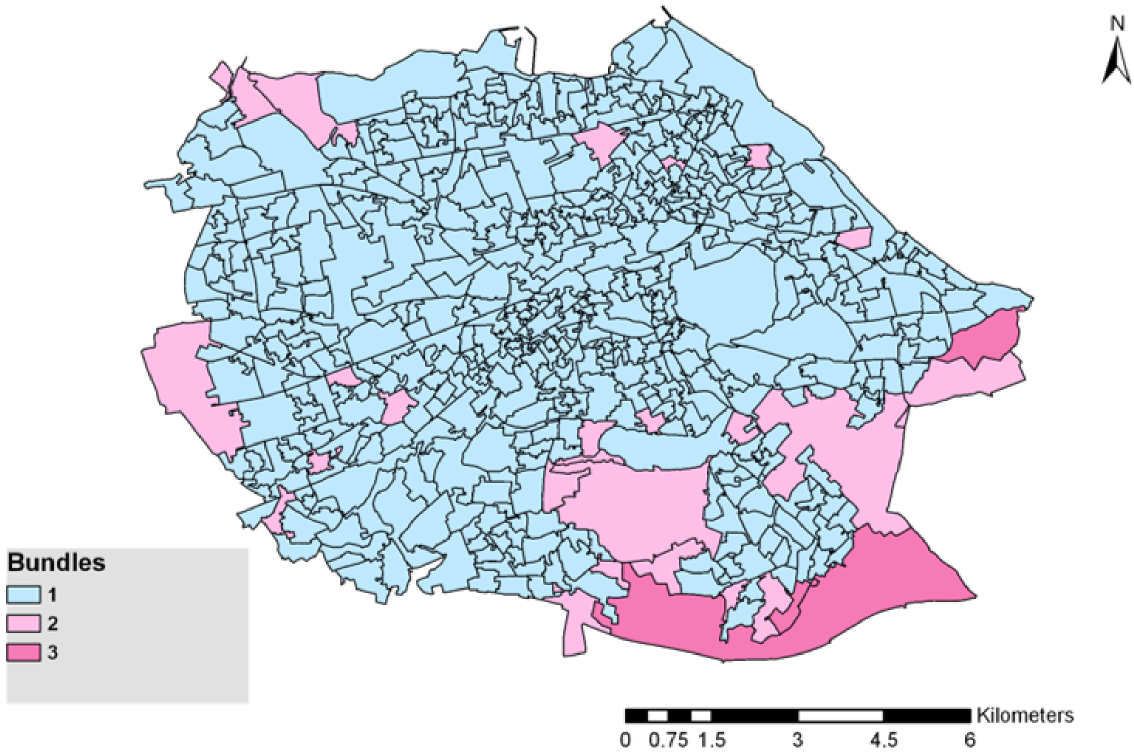

Figure 3.13: Map of the three clusters identified with the NI dataset. NIE and NIM lead to similar distributions.

3.6.5.2 Ymca

Ymca, the three-bundle solution obtained after transformation, scoring and MCA projection on two components, identifies three distinct levels of provision of ES across the city (3.12 above). It shows a gradient G of provision from G1 to G3 for all services except for Food Growing and Contribution to Physical Activity, which keep a similar median across all bundles. The other medians vary in a range from -2 to 4 MAD units. The gradient is more severe for Run-Off Retention, Temperature Regulation and Contribution to Mental Health in the decrease from bundle G2 to bundle G3, compared to Air Purification, Carbon Storage, Noise Attenuation and Habitat Provision (Figure 3.14). The reverse is true for the decrease from G1 to G2. The differences between these two groups of services is in line with the ES Bundles identified in section 3.5, which places them in different groups.

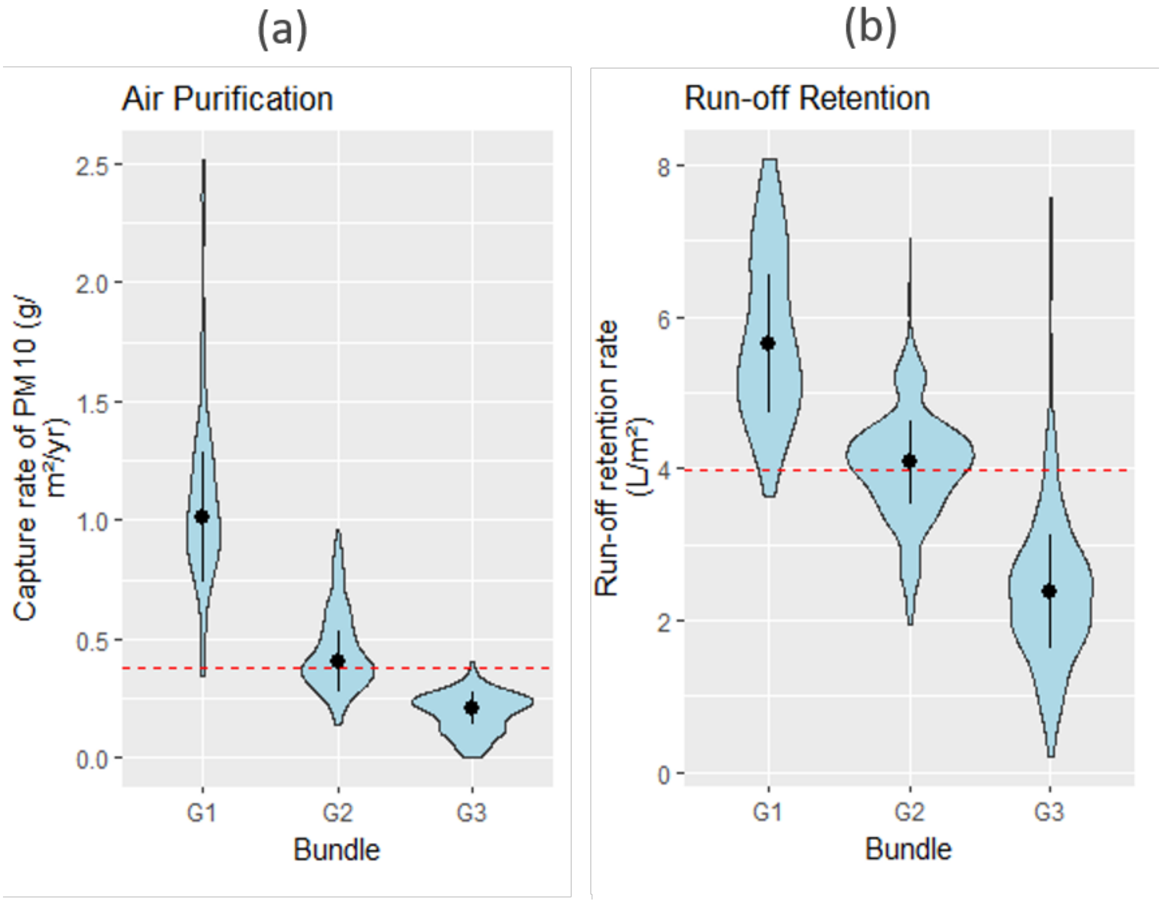

Figure 3.14: Violin plots for Run-Off Retention and Air Purification, broken down by Ymca bundle. The decrease from G1 to G2 is sharpest for Air Purification, while the decrease from G2 to G3 is sharpest for Run-off Retention.

3.6.5.3 YRh

YRh is also a three-bundle solution, which was obtained after transformation, range standardisation and a projection conserving Hellinger distances. Two bundles represent two distinct levels of provision for all services except for Food Growing and Contribution to Physical Activity: they are called G1 and G2 in line with the gradient ("G") terminology used for Ymca (Figure 3.15). The third bundle is mainly characterised by a higher than average provision of Food Growing (Figure 3.15): a closer look shows that it holds 94% of Food Growing's non-zero values (average is understood here in the 'median' sense). This bundle was named F to indicate the predominance of Food. The level of provision of all other services in bundle F are similar to their provision in bundle G1, as shown in the violin plots (Appendix D.4). The spatial distribution of YRh bundles confirms that bundle F was assigned to data zones 'regardless' of their values for any other service than Food Growing, as the configuration of bundles drastically differs from the gradient identified by Ymca (Figure 3.16).

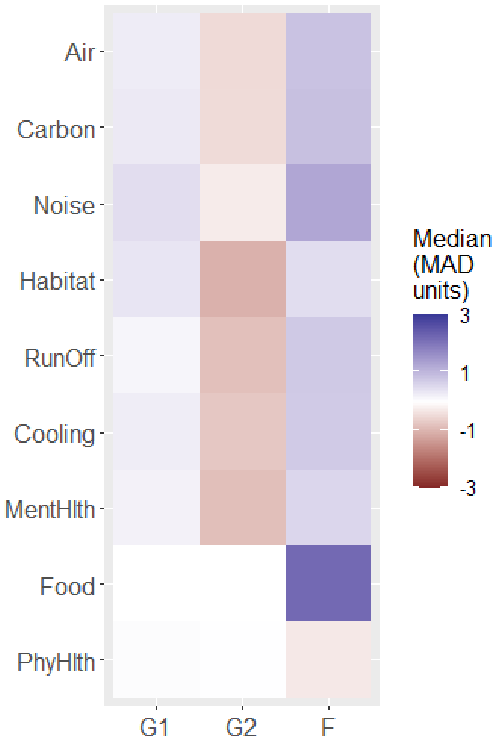

Figure 3.15: Heatmap showing YRh bundles.

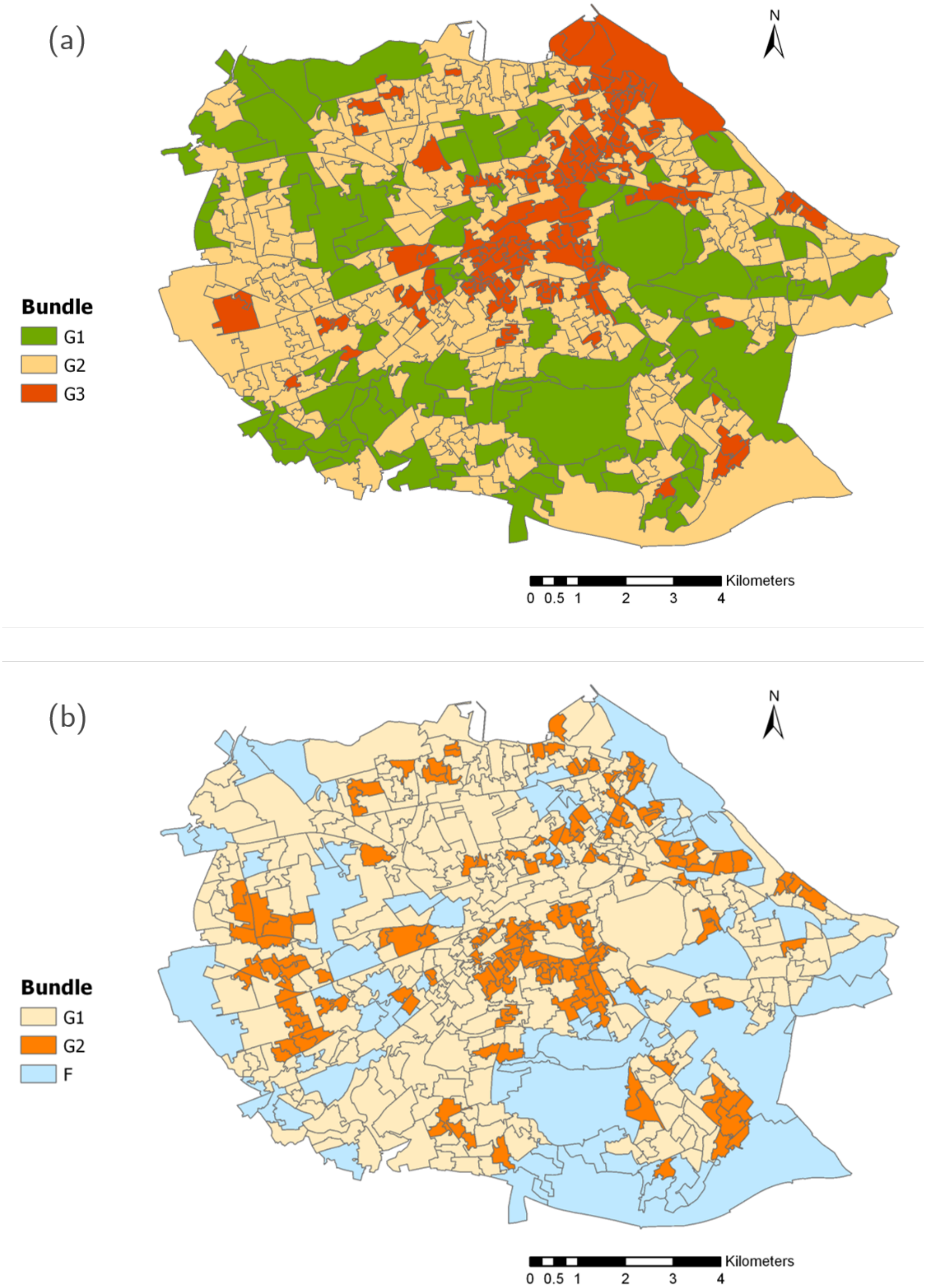

Figure 3.16: Maps comparing the spatial distributions of (a) Ymca bundles and (b) YRh bundles. The gradient of provision identified with the Ymca dataset is not visible in the YRh map, while the differences in Food Growing do not appear in the Ymca map.

3.6.5.4 Nmca

Nmca, the five-bundle solution obtained without transformation, scoring and MCA projection on two components, identifies five distinct levels of provision of ES across the city (Figure 3.17). Like Ymca, it shows a gradient of provision for all services except Food Growing and Contribution to Physical Activity. Similarly, the differences across the higher provision bundles are greater for the group "air purification - noise attenuation - carbon storage - habitat provision" than for the group "run-off retention - temperature regulation - contribution to mental health", while the reverse is true for the lower provision bundles. As mentioned for Ymca, the differences between these two groups of services is in line with the ES Bundles identified in section 3.5. Maps of the spatial distributions of Nmca and Ymca show similar patterns (Figure 3.18) and their contingency table confirms the relationship between the two solutions (Figure 3.19): Nmca's bundle G5 corresponds to Ymca's bundle G3, while Nmca's bundles G1 and G2 constitute a split of bundle Ymca's bundle G1. Similarly, Nmca's bundles G3 and G4 constitute a split of bundle Ymca's bundle G2. Nmca therefore does not 'reshuffle' the bundles identified by Ymca but rather provides an additional level of detail.

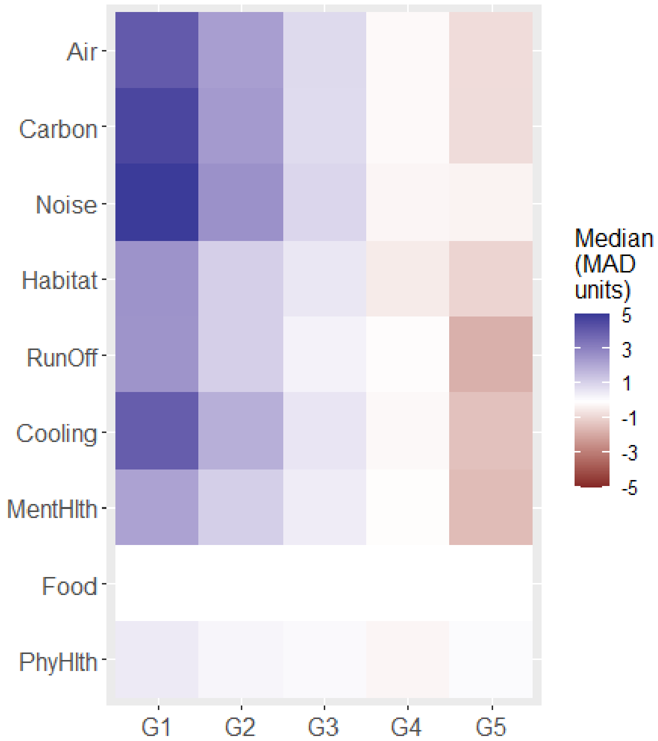

Figure 3.17: Heatmap showing Nmca bundles.

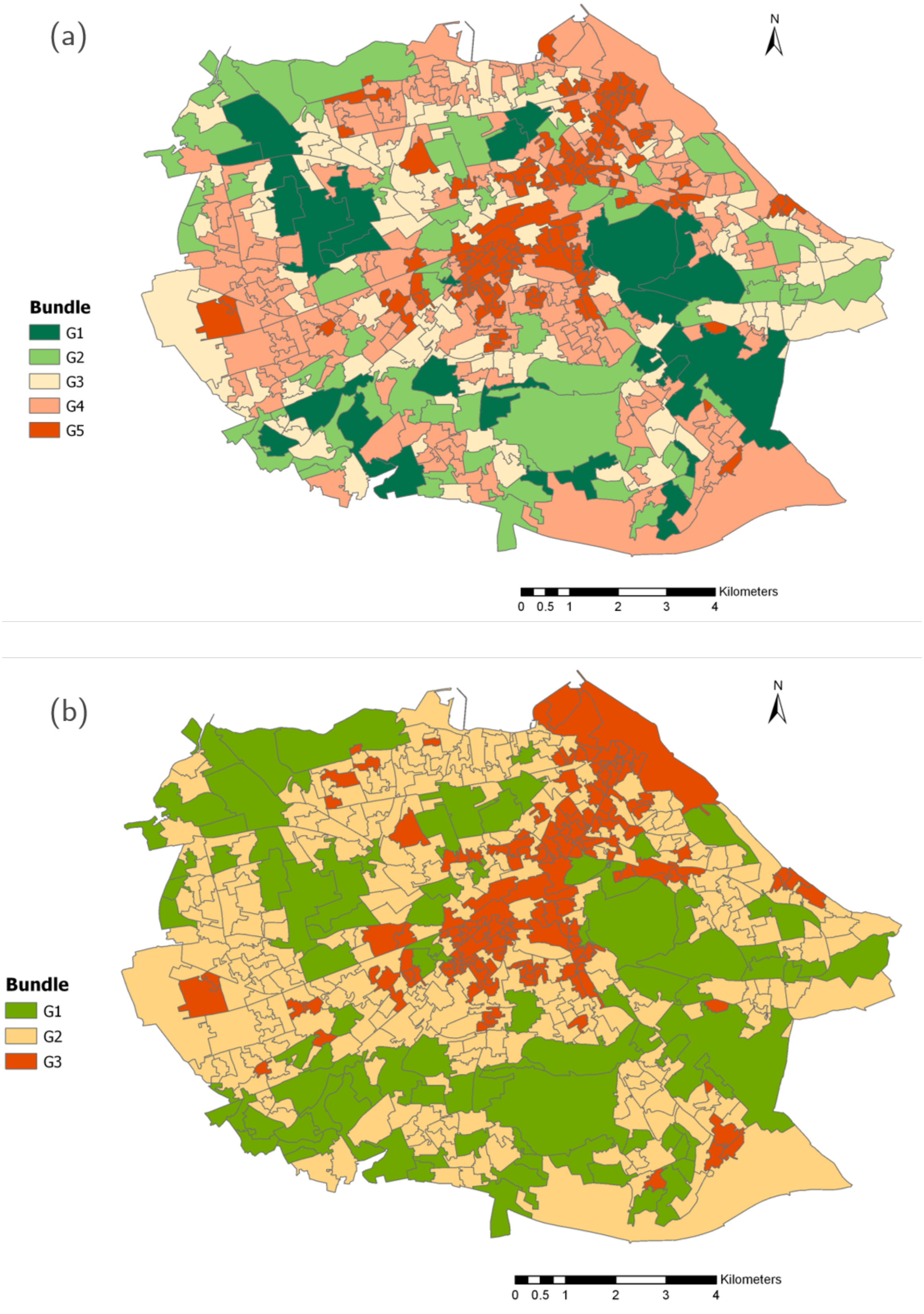

Figure 3.18: Maps comparing the spatial distributions of (a) Nmca bundles and (b) Ymca bundles. Nmca bundles provide more details for the areas corresponding to Ymca's G1 bundle.

Ymca \ Nmca	G1	G2	G3	G4	G5
G1	27	60	2		
G2		3	121	190	1
G3				29	125

Figure 3.19: Contingency table of Nmca and Ymca, displaying the number of common data zones for each pair of bundles.

3.6.5.5 YME

YME is the five-bundle solution obtained after transformation, median z-score standardisation and a projection conserving Euclidean distances. Bundles G1 to G4 represent four distinct levels of provision for all services except for Food Growing and Contribution to Physical Activity, while bundle F is mainly characterised by a higher than average provision of Food Growing, as well as a lower than average Contribution to Physical Activity (average is understood here in the 'median' sense) (Figure 3.20). The level of provision of all other services in bundle F are similar to their provision in bundle G2, as shown in the heat map and the violin plots (Appendix D.4). Similar to Ymca and Nmca, the differences across the higher provision bundles are greater for the group "air purification - noise attenuation - carbon storage - habitat provision" than for the group "run-off retention - temperature regulation - contribution to mental health", while the reverse is true for the lower provision bundles. The differences between these two groups of services is in line with the ES Bundles identified in section 3.5.

A comparison between YME and Nmca using their respective spatial maps and a contingency table shows that bundles G2 to G4 (G3 to G5 for Nmca) can be considered stable across both solutions, while bundles F and G1 (G2 and G1 for Nmca) are reconfigured by the introduction of a bundle determined by Food Growing in

YME (Figures 3.21 and 3.22). This has two implications. First, where two levels of high provision were identified by Nmca (G2 and G1), only one subsists in YME (G1); second, data zones which are considered similar by Nmca in bundle G1 to G4 even though they differ by their level of Food Growing, are picked out by YME. Furthermore, YME is similar to YRh in that they both feature a bundle characterised by a high level of Food Growing; however, they differ in that YME does not reshuffle all bundles identified by Ymca and Nmca.

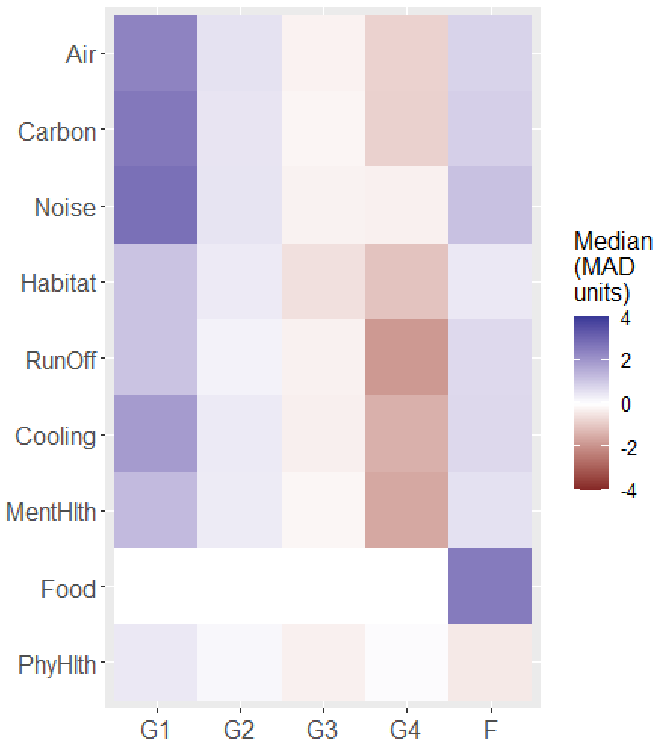

Figure 3.20: Heatmap showing YME bundles.

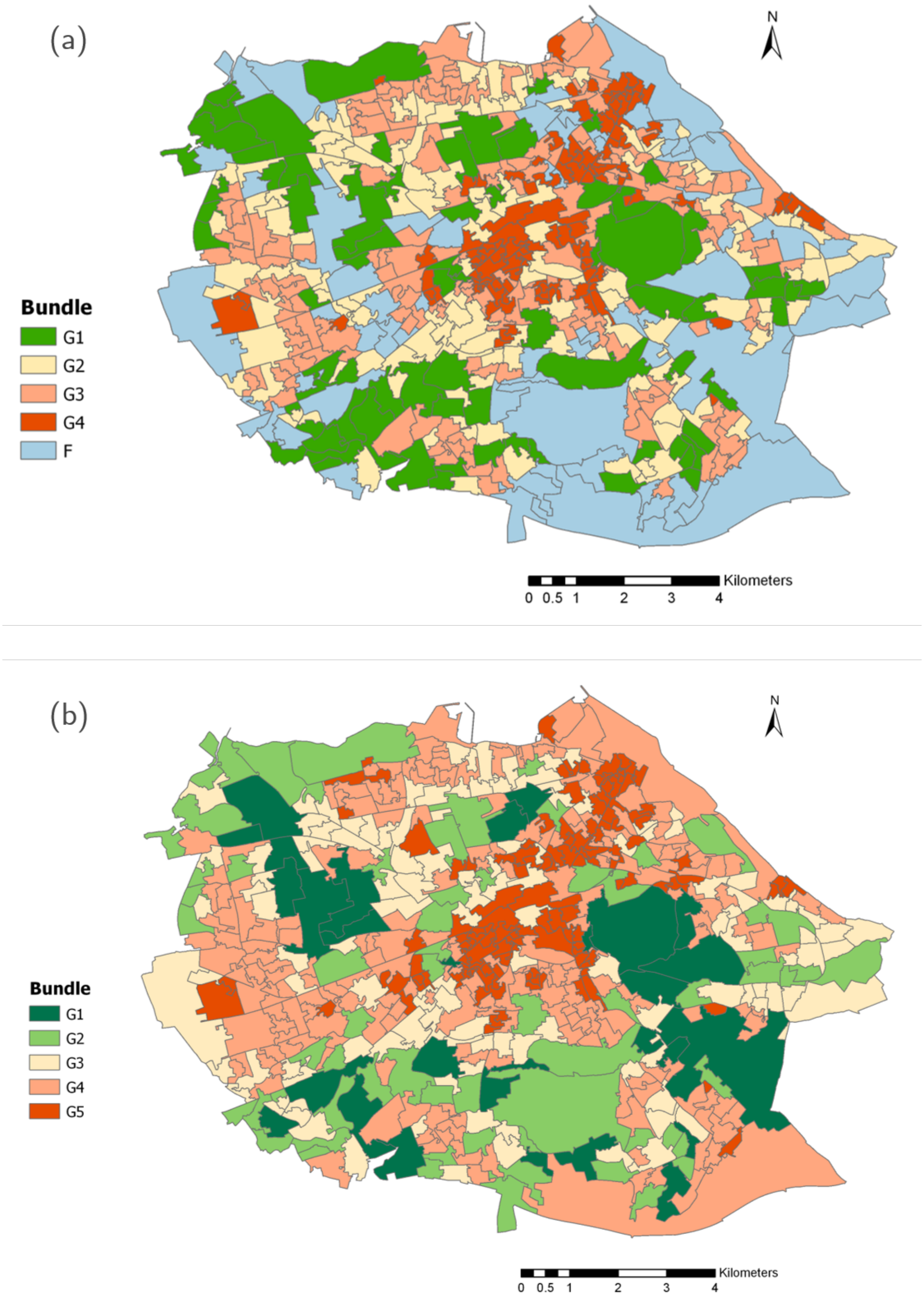

Figure 3.21: Maps comparing the spatial distributions of (a) YME bundles and (b) Nmca bundles.

YME / Nmca	G1	G2	G3	G4	F
G1	17				10
G2	46				17
G3	12	93	3		15
G4		40	155	5	19
G5			15	108	3

Figure 3.22: Contingency table of YME and Ymca, displaying the number of common data zones for each pair of bundles.

3.6.5.6 NME

NME is the 8-bundle solution obtained after median z-score standardisation and a projection conserving Euclidean distances. Bundles G1 to G5 represent five distinct levels of provision for all services except for Food Growing and Contribution to Physical Activity. Similar to Ymca, Nmca and YME, the differences across the higher provision bundles are greater for the group "air purification - noise attenuation - carbon storage - habitat provision" than for the group "run-off retention - temperature regulation - contribution to mental health", while the reverse is true for the lower provision bundles. The differences between these two groups of services is in line with the ES Bundles identified in section 3.5

Bundle F1, F2 and F3 are mainly characterised by a higher than average provision of Food Growing, as well as a lower than average Contribution to Physical Activity (average is understood here in the 'median' sense) (Figures 3.23 and 3.27). Food Growing and Physical Activity vary in opposite directions from F1 to F3, which is consistent with their relative position in the ES bundles space (section 3.5). The other services take two different levels of values in F2 and F3: values in F2 are similar to those in G2 while those in F3 are similar to those in G3. F1 contains only three data zones and services other than Food Growing and Contribution to Physical Activity do not follow a trend. NME's spatial map and its contingency table with Nmca shows that both solutions identified a similar 5-level gradient of ES provision (Figures 3.24 and 3.25). However, NME's additional three bundles allow to single out the data zones with the highest levels of Food Growing.

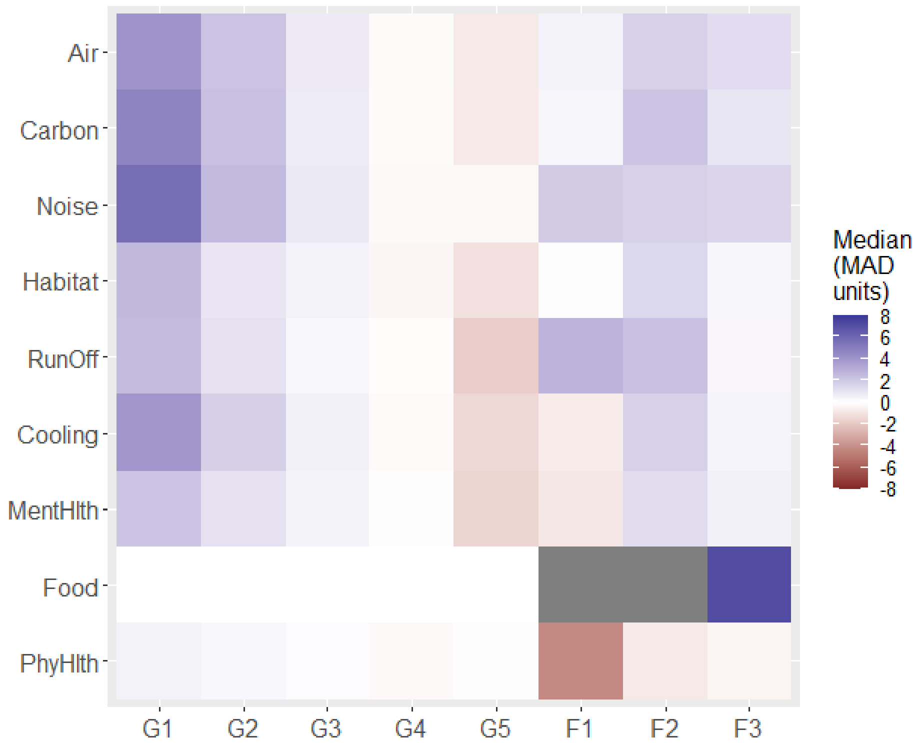

Figure 3.23: Heatmap showing NME bundles. The Food Growing levels are out of bounds for F1 and F2, at respectively 91.3 and 33.5. See Figure 3.27 for a full plotting of the NME ES profiles.

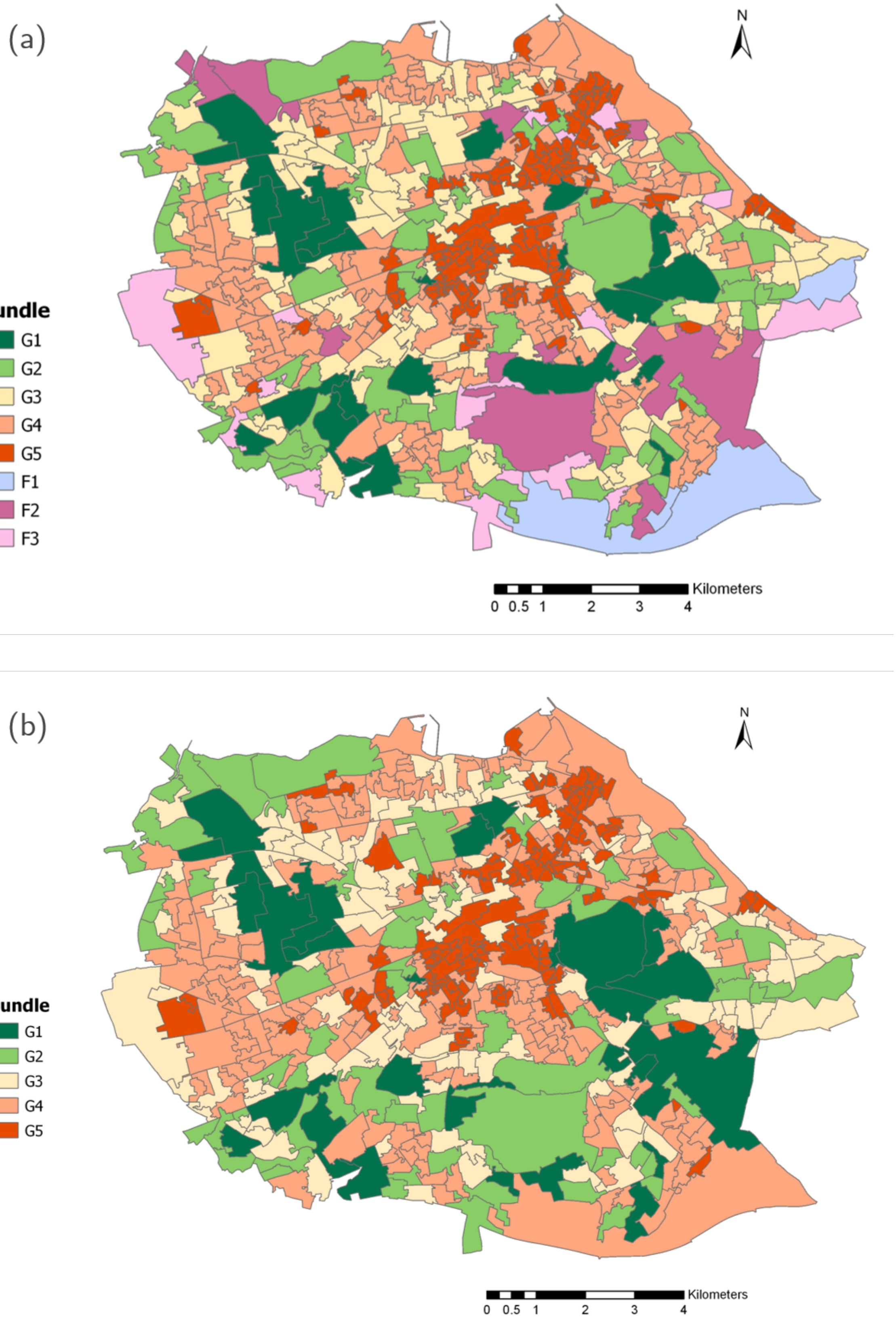

Figure 3.24: Maps comparing the spatial distributions of (a) NME bundles and (b) Nmca bundles. A similar gradient is represented by both solutions.

NME / Nmca	G1	G2	G3	G4	G5	F1	F2	F3
G1	20	1	1				3	3
G2	3	51	1			1	4	3
G3		8	108	3			1	5
G4			16	183	11	2	2	5
G5				8	118			

Figure 3.25: Contingency table of NME and Ymca, displaying the number of common data zones for each pair of bundles.

3.6.6 Validation and description of the optimal bundle solution

3.6.6.1 Selecting an optimal bundle solution

The identification of gradients of ES provision across the bundle solutions matches the finding from ES bundles that most ES are synergetic and vary together (section 3.5). The bundle solutions identify two to five levels in the gradient depending on the space in which they were computed. The three-, four- and five-level solutions correspond to a similar gradient, with the five-level solutions identifying a finer yet still coherent partition of the data zones along the gradient. The five-level solutions, Nmca and NME, were both obtained using a non-transformed dataset, while the other solutions were based on a transformed dataset (see Figure 3.26). This can be explained by the compressing effect of the transformation step, which hid variations in the higher values. This is confirmed by the fact that the splits leading to four- and five-level solutions occur for bundles corresponding to high provisions of ES (see for example the relationship between Ymca and Nmca). It also shows that in this case study, the structure underlying the lower values did not need transformation to be apparent to the PAM clustering algorithm. The two-level solution, YRh, does not correspond to the same gradient as the others (see for instance Figure 3.16), as clustering occurred primarily in relation to the level of Food Growing, and grouped data zones with different profiles regarding the other services into the same bundle. Although this phenomenon also takes place for YME and NME (respectively a five-bundle (four-level) solution and an eight-bundle (five-level) solution), it is particularly severe for YRh because of its low number of bundles (three). The very high variation in the distribution of Food Growing (Table 3.9) explains its impact on bundles identified from datasets which have not been scored. Datasets which have been scored are not influenced by the high variability on Food Growing because most of the variation is hidden within the highest score (Table 3.11). This is also true, to a lesser extent, for the Contribution to Physical Activity.

Number of bundles \ Number of gradient levels	**2**	**3**	**4**	**5**
3	YRh*	Ymca	-	-
5	-	-	YME*	Nmca
8	-	-	-	NME*

Figure 3.26: Categorisation of the potential bundle solutions according to their number of bundles and the number of gradient levels they identify. Starred solutions are the ones featuring bundles characterised by a higher provision of Food Growing (and potentially lower Contribution to Physical Activity). Only non-transformed datasets identify a 5-level gradient.

Table 3.11: Range of the proportion of land area dedicated to food growing, by score. The eighth and last level gathers most of the variation.

Score	Range
1	[0.0, 0.0038[
2	[0.038, 0.011[
3	[0.011, 0.019[
4	[0.019, 0.027[
5	[0.027, 0.034[
6	[0.034, 0.042[
7	[0.042, 0.50[
8	[0.050, 0.70[

The ultimate choice of a bundle solution is a compromise between the number of bundles, the level of detail in the gradient and the impact of Food Growing. Because bundles are not reshuffled when increasing the level of gradient detail (with the exception of YRh), therefore representing a similar pattern, the finer partitions are preferred: Nmca and NME. Because the influence of Food Growing in shaping NME's bundles does not prevent the identification of significant patterns for the other services, as was the case for YME and YRh, this solution seems to be a good compromise.

3.6.6.2 Description of the selected solution

The NME solution is reproduced in Figure 3.27, using barplots instead of heatmaps and more explicit bundle names derived from the qualitative description laid out in this section.

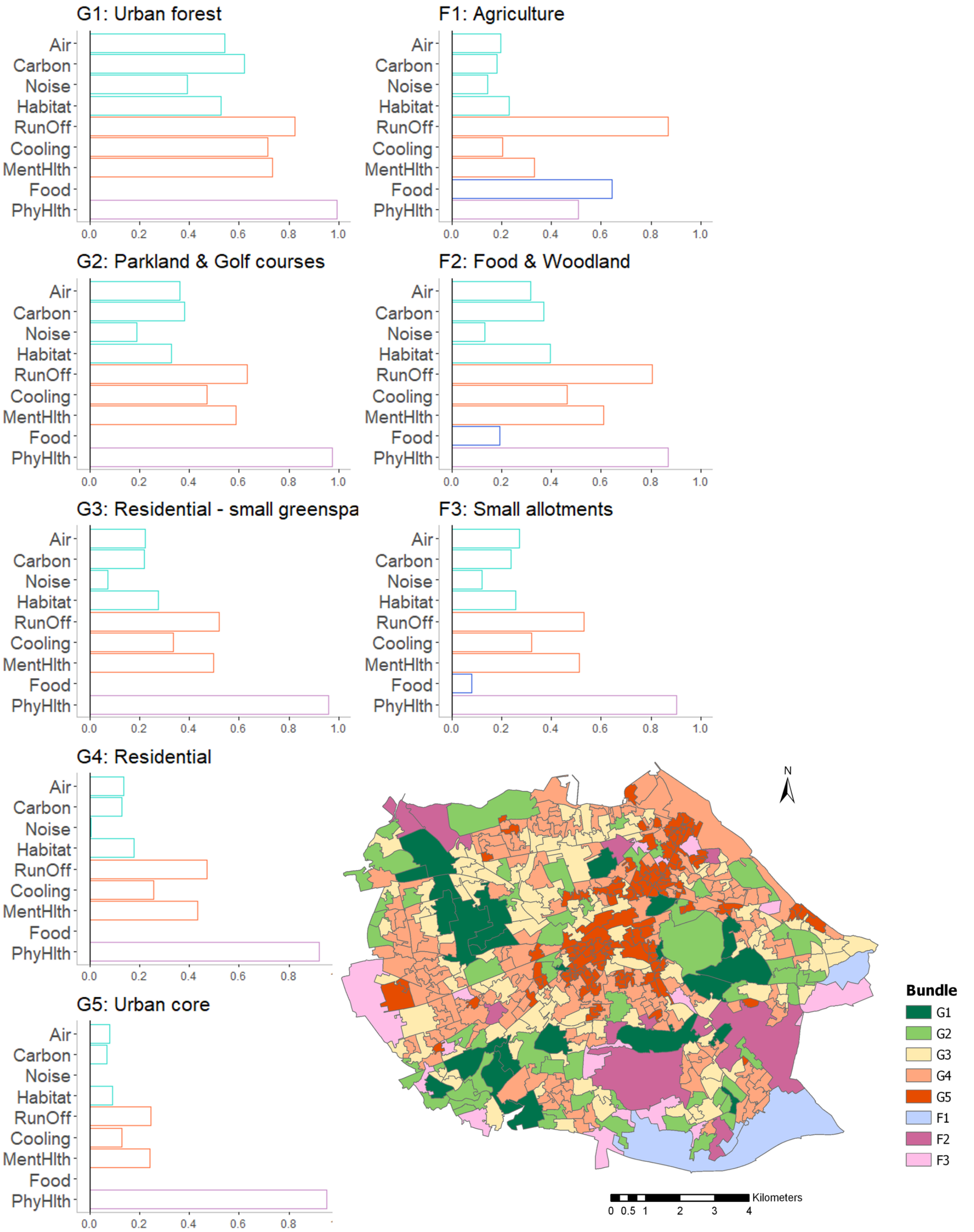

Figure 3.27: Bundle map of the selected solution and bar plots showing the ES profile of each Spatial Bundle. The bar plots represent the median of the range-standardised ES values in each bundle. The bar colours refer to the four ES Bundles identified in section 3.5.

The lowest levels of provision in the NME gradient, identified by bundle G4 and G5

(Figure 3.23), cover 323 out of the study's 558 data zones. This coverage corresponds to 33% of the study's area but 58% of its population, showing that areas with a lower ES provision are also more dense. Areas characterised by a G5 profile are mostly located in the city centre all the way to Leith, while G4 data zones can be found in various locations across the City (Figure 3.24). For instance, Parkhead and Clermiston in the West, as well as Craigour and Moredun in the South and Restalrig in the North, have a similar G4 profile. The fact that ES values in G4 and G5 are positioned below the overall median, even though they gather a majority of data zones and residents, points to a 'hotspot' effect where a minority of data zones provide relatively high values of ES.

These 'hotspots' are clearly visible in Figure 3.24 in dark green (G1), light green (G2) and dark purple (F2). They represent the City's large parks and golf courses, as well as greenspace along the Water of Leith and the Burdiehouse Burn. This result shows the importance of large greenspaces with woodland and semi-natural areas for obtaining high levels of multiple benefits. This is partly due to the fact that some ES have land cover thresholds below which very little or none of it is provided.

Areas with a G3 profile are characterised by a level of ES provision sitting around the overall median, below levels displayed by data zones covered by large greenspaces. In G3 areas, vegetated paths, such as Blackhall Path and Ferry Road Path, combined with small greenspaces and a network of private gardens, ensures a level of provision that is higher than most data zones (those in G4 or G5 areas), without relying on large areas of woodland and semi-natural areas. Areas with an ES provision similar to G3 but including some level of food growing are gathered in bundle F3: they point to areas where small greenspaces are complemented with spaces for community growing. The G3 profile is interesting because it shows the importance of networks of smaller natural spaces in providing ES in places where it may not be feasible to introduce large greenspaces.

The F1 profile only describes 3 data zones, which are characterised by large agricultural areas in the South, East and North of the city. These areas show high levels of food growing (crop or grazing) and run-off retention, but low levels of provision of other ES.

Based on the qualitative description of the bundles laid out above, I suggest a more explicit, yet simplified, denomination of the different profiles (Figure 3.27):

- G1: "Urban forest"
- G2: "Parkland & golf courses"
- G3: "Residential - small greenspace"
- G4: "Residential"
- G5: "Urban core"
- F1: "Agriculture"
- F2: "Food & Woodland"
- F3: "Small allotments"

The next section further analyses this set of Spatial Bundles by investigating the potential factors predicting their delineation.

3.7 Identification of drivers

3.7.1 Selection of potential predictors

Spake et al. (2017) mention the importance of testing specific hypotheses about specific predictors in order to robustly identify drivers. This subsection addresses the pre-selection of such predictors based on their expected influence on the formation of bundles.

The analysis of ES bundles, presented in section 3.5, allows to qualitatively infer the importance of two factors:

- **Soil sealing**, which seems to discriminate between Bundle 3 on the one hand and Bundles 1 & 2 on the other hand;
- **Tree cover**, which seems to discriminate between Bundle 1 and 2.

Besides, these two parameters are aspects which can be acted upon at urban planning level, making them potentially salient from a practitioner perspective.

Another aspect which is characteristic of urban areas and could influence the formation of bundles is **population density**. By including this aspect in the prediction process, I am testing whether the difference in data zone density can predict bundle assignation.

The specific variables associated with these three potential predictors are:

- The percentage of tree cover, which includes the attribute values specified in Table 3.3 as well as the the percentage of trees typically present in Private Gardens (Table 3.8).
- The percentage of sealed areas, defined by any area which is not covered by vegetation, water or agricultural land. The percentage of sealed areas in typical Private Gardens was also included.
- The population density as reported in Scottish Government (2019*a*) and converted in 1000 $hab.km^{-2}$.

Their influence is explored using Multinomial logistic regression (MLR) and Classification And Regression Trees (CART).

3.7.2 Multinomial logistic regression (MLR)

Before conducting the regression, multicollinearity is tested by computing simple correlations among the variables (Table 3.12). Although they are not strictly independent, their levels of correlation < 0.7 allow to hypothesise that multicollinearity is not an issue in this case. It will be tested by checking whether the regression coefficients are counter-intuitive (e.g. the model predicts that ES are provided at a higher level in highly sealed areas) and whether the regression coefficients vary drastically when removing one or more variables.

Table 3.12: Correlations between the three tested predictors. All values are significant at $p<0.001$

	%Tree	%Sealed	Pop density
%Tree	1		
%Sealed	-0.59	1	
Pop density	-0.41	0.63	1

A dataset is created by collating the three tested predictors and the vector containing the bundle assignation. It is then split into a training and a testing dataset, by creating two samples stratified according to their bundle value, with the training set containing 75% of the data. Stratification was conducted using the *stratified* function of the *splitstackshape* package (Mahto 2019).

Multinomial logit regression is performed using the *multinom* function of the *nnet* package (Venables & Ripley 2002). Bundle G5 is chosen as the reference bundle, i.e. the one in relation to which the model will assess the likelihood of obtaining any other bundle depending on the tested predictors. Choosing G5 as a baseline is justified because it gathers the data zones with the lowest level of ES provision: the model will give information on the extent to which an increase in the tested predictors leads to an increase in the likelihood of obtaining a bundle associated with a higher provision of services than G5.

A regression model is computed for each of the tested predictors and all of their combinations. Results of these models are then used to predict bundle assignation for the testing set: contingency tables comparing the predicted with the actual bundle assignations allow to assess the accuracy of the models: the simplest model with the highest accuracy is obtained with the variables "percentage of tree cover" and "percentage of sealed area" (Table 3.13). These parameters can therefore be considered as the main drivers for bundle formation. The log-odds resulting from the model predicting bundle outcome using the two identified drivers are presented in Table 3.14.

Table 3.13: Accuracy of the regression models obtained with different combinations of the tested potential predictors. Tree = Percentage of tree cover; Sealed = Percentage of sealed area; dPop = Population density. Accuracy was calculated from contingency tables obtained on a testing set.

Tested predictors	Accuracy
Tree + Sealed + dPop	82%
Tree + Sealed	82%
Tree + dPop	75%
Sealed + dPop	54%
Tree	68%
Sealed	51%
dPop	46%

Table 3.14: Regression coefficients of the MLR model. They correspond to the log-odds of obtaining bundles F1 to F3 and G1 to G4 against the baseline G5. All values are significant at $p<0.001$ using Wald tests (Fahrmeir et al. 2003)

	Tree	Sealed
F1	3.33	-1.59
F2	4.05	-0.76
F3	3.74	-0.62
G1	4.51	-0.76
G2	4.14	-0.68
G3	3.65	-0.58
G4	2.37	-0.39

Log-odds are positive for tree cover and negative for sealed area, which means that the probability of getting any bundle compared to bundle G5 increases with tree cover and decreases with sealed area. Furthermore, absolute values of log-odds for tree cover are higher than those of sealed area, which means that tree cover variation has more influence on bundle formation than variation in sealed area. Although all coefficients are significant, the low frequencies of bundles F1 to F3 in the dataset means that the capacity of the model to predict assignation to these bundles is not as good as for the others (Table 3.15).

Table 3.15: Contingency table between predicted and actual bundles for the testing set of the selected MLR model (n=138 data zones, accuracy = 82%). F1 to F3 could not be accurately predicted.

	F1	F2	F3	G1	G2	G3	G4	G5
F1						1		
F2	1			1				
F3				1	2	1		
G1				5	1			
G2		1			13			
G3					1	25	5	
G4						1	43	4
G5							3	29

A useful way to understand the model is by computing the predicted probabilities for each bundle and plotting them as functions of the two drivers. For instance, one can plot the predicted probabilities against the percentage of sealed areas by different levels of tree cover and for each bundle. Such plots are introduced at the end of this section.

3.7.3 Classification and Regression Trees (CART)

A CART model predicting bundle assignation according to the two main drivers is determined using a cross-validation method - implementation in R is done with the *rpart* and *caret* packages (Therneau & Atkinson 2019, Kuhn 2019). A 10-fold cross validation method is used and the tested complexity parameters range from 0 to 0.20 with a 0.01 increment. Figure 3.28 shows the tree corresponding to the best model, which has an 75% accuracy on the testing set.

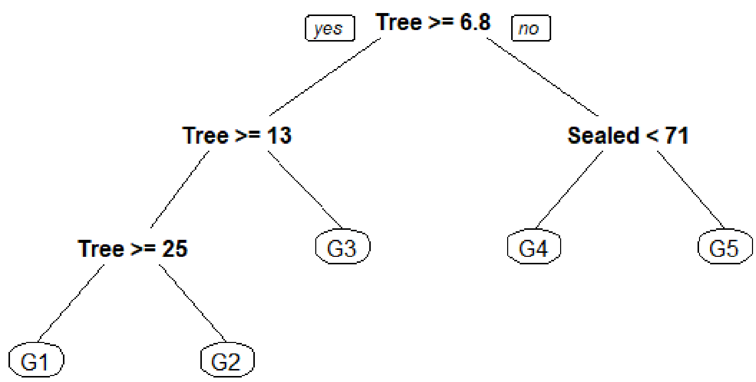

Figure 3.28: Plot of CART model. Tree = Percentage of tree cover; Sealed = Percentage of sealed area.

Figure 3.28 can be interpreted as a decision tree assigning bundles depending on values taken by the percentage of tree cover and the percentage of sealed area. The tree shows that the CART model does not allow to predict bundles F1 to F3, due to their low frequency. The majority of nodes are characterised by conditions on tree cover, which confirms the predominance of this driver compared to sealed area, a phenomenon also identified with multinomial regression. In particular, a data zone being assigned G1, G2 or G3 by the CART model depends on its tree cover only and the amount of sealed area does not play a role (the three left-most branches in Figure 3.28). The sealed area threshold value identified by the model (71%) allows to distinguish between G4 and G5.

The threshold values determined for tree cover can be used to identify relevant levels for which to plot the probabilities predicted by the multinomial regression model. This will allow to compare both models more deeply and to produce a relevant visualisation of the multinomial model.

3.7.4 Bringing MLR and CART together

Probabilities predicted by the MLR model are plotted against the percentage of sealed area, by bundle, and for different proportions of tree cover (Figure 3.30). These proportions are chosen based on the different branches of the CART model and are set at 3%, 10%, 20% and 30% (Figure 3.29).

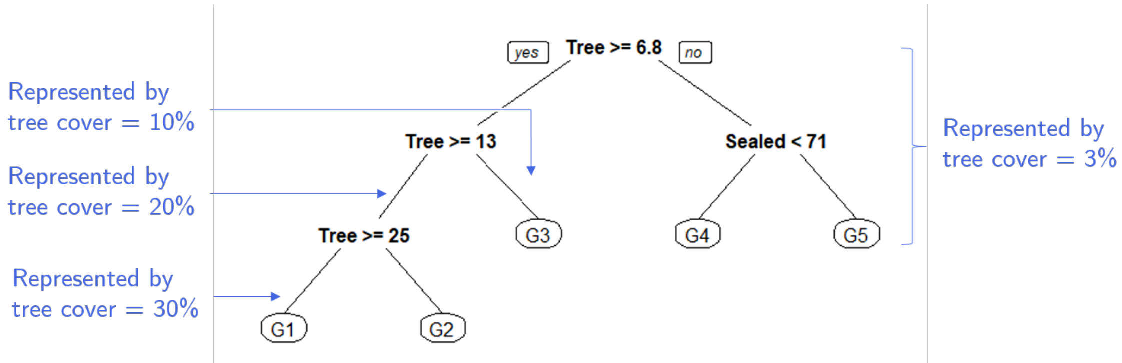

Figure 3.29: Selection of tree cover proportions at which to plot the probabilities of bundle assignment.

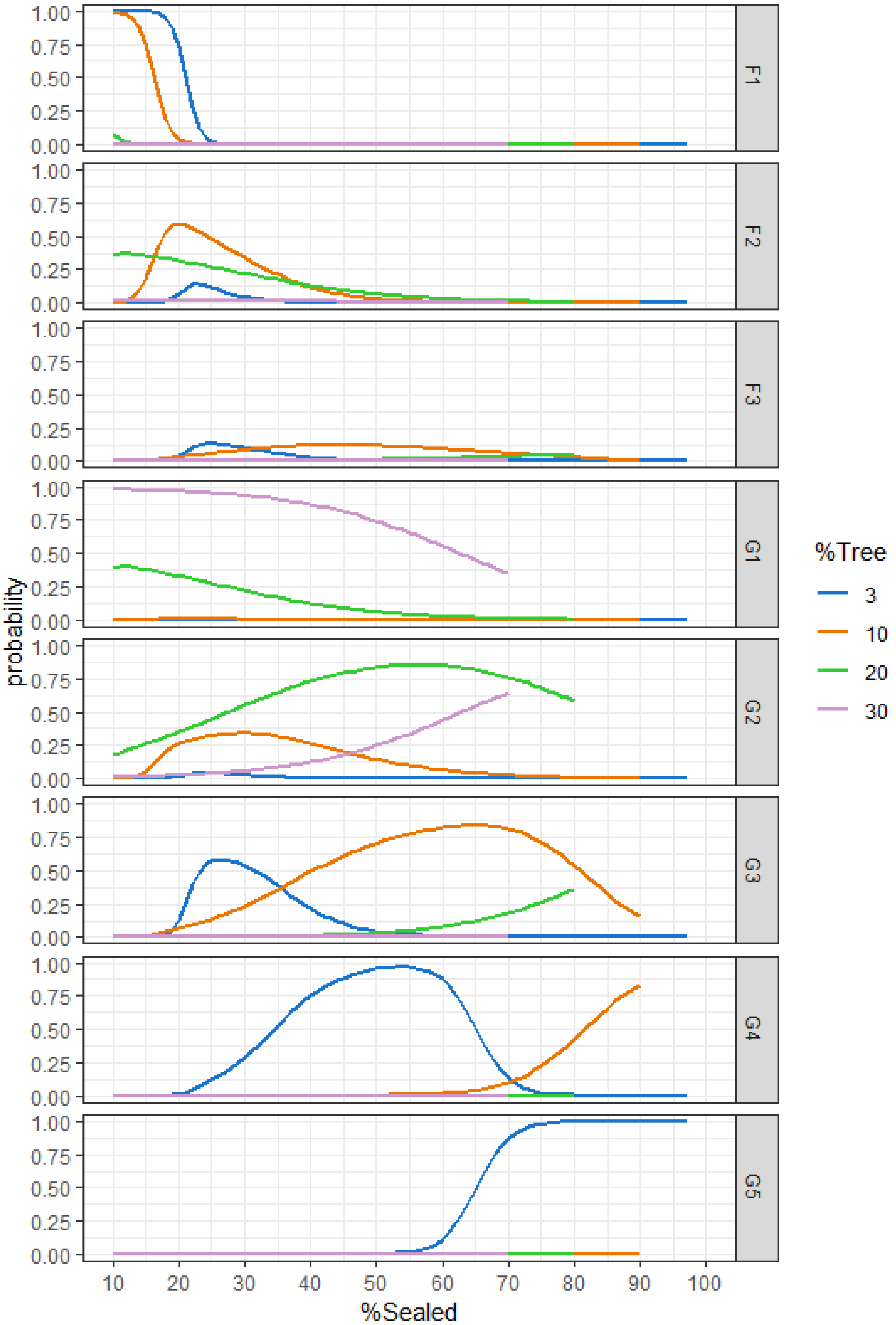

Figure 3.30: Probability of bundle outcome plotted against the percentage of sealed area for four levels of tree cover (3%, 10%, 20%, 30%).

3.7.4.1 Data zones with a percentage of tree cover of 3%

For a percentage of tree cover of 3%, the model predicts three main different assignations depending on the percentage of sealed area. Where less than 20% of the land is sealed, food growing bundle F1 is the most probable: the model therefore correctly attributes a food growing bundle to areas characterised by a high proportion of unsealed, unwooded areas, typical of the presence of large agricultural land. However, predictions of food bundles should be interpreted with precautions because of the small sample size in the Edinburgh dataset and the failure of the model to predict them in the testing dataset (Figure 3.15).

In contrast, data zones with sealed cover higher than 20% are mostly characterised by either one of the two lowest gradient bundles, G4 and G5. The most probable bundle is G4 if the percentage of sealed area is lower than around 60%, and G5 if higher. This last result partly matches the results from the CART model, which predicts G4 and G5 as the two only possible outcomes, but puts the pivot value of sealed area at 71%.

3.7.4.2 Data zones with a percentage of tree cover of 10%

For a percentage of tree cover of 10%, four main cases can be identified depending on the level of sealing:

1. Below 15%;
2. Between 15% and 40%;
3. Between 40% and 80%;
4. Above 80%.

Where less than 15% of the land is sealed (case 1), food growing bundle F1 is the most probable, in a similar way it was for data zones with 3% of tree cover. The same caveat about the capacity of the model to actually predict such a bundle applies here too.

Where more than 15% of the land is sealed, data zones with a 10% tree cover can have different profiles depending on the level of sealing they experience. The model predicts either food growing bundle F2 or gradient bundle G2 when sealing is kept below 40% (case 2). These two bundles have similar, relatively high levels of provision of all services with the exception of food growing and physical activity (see heatmap in Figure 3.23). It is more probable to get F2 than it is to get G2, meaning that a tree cover of 10% associated with low levels of sealing might‘ be more characteristic of agricultural land than it is of other types of urban form. In contrast, data zones with levels of sealing higher than 40% cannot be assigned any food growing bundle. If they have unsealed cover other than trees (case 3), the model predicts an ES profile characteristic of bundle G3; if they do not, a profile characteristic of G4 (case 4). A profile consistent with G3 involves a slightly higher than average provision of most ES, while G4 features lower levels. It is worth noting that a proportion of trees of 10% cannot result in the lowest gradient bundle (G5).

These results are partly supported by the CART model, which predicts bundle G3 for any level of sealing. In Edinburgh for instance, more than 80% of data zones have sealing levels in the 40% to 80% range, which means that the MLR model would effectively predict a G3 bundle for a majority of data zones, in accordance with the CART model.

3.7.4.3 Data zones with a percentage of tree cover of 20% and 30%

For a percentage of tree cover of 20%, the most probable bundle is G2, which matches the results from the CART model.

For a percentage of tree cover of 30%, the most probable bundle is G1 - however, for values of sealed area close in the 60%-70% range, it is almost equally probable to get G1 or G2. The CART model identifies G1 as the only possible outcome for any value of sealed area, which partly matches the predicted probabilities.

3.7.4.4 The role of predictors as interpreted from the models

Obtaining a bundle outcome characteristic of a relatively high provision of ES mainly depends on tree cover - in our case one higher than around 13% (see Figure 3.28). Nevertheless, areas where tree cover is poor may also provide a higher than average level of ES, but only if sealing levels are kept very low (below 20%). These areas are characteristic of agricultural land.

At the other end of the spectrum, a very low provision of ES (consistent with bundle G5) can only occur in data zones where tree fractions are lower than around 7%. However, the MLR model shows that the reverse is not true: food growing bundles might still be obtained at very low levels of sealing; furthermore, where sealing is around 50%-60%, the most probable bundles are G3 and G4, which are higher than G5 in the ES gradient.

More generally, bundles G3 and G4 are the most frequent in the Edinburgh dataset. Their levels of ES are around the overall median, although bundle G3 is associated with higher levels than G4 (see heatmap and violin plots). They can only occur for tree cover fractions lower than around 13% and correspond to a variety of tree cover and soil sealing conditions. Therefore, when tree cover is lower than 13%, different types of land structure lead to similar levels of provision of ES (land structure is defined here by the two parameters tree cover and soil sealing). For instance, a data zone characterised by a percentage of sealed area of 50% and a tree cover of 3% is highly likely to belong to bundle G4, as would a data zone characterised by a percentage of sealed area of 90% and a tree cover of 10%.

Bundle F3 is the least probable: it is not predicted by the CART model and its maximum probability according to the MLR model sets at 0.14 (all other bundles reach at least 0.40) (Table 3.16). It may occur when levels of sealing are lower than 60%. Food growing bundles in general are not well predicted by the two main drivers, as mentioned in the previous subsections.

Table 3.16: Maximum probability of occurrence of each bundle, calculated with the MLR model on the training set.

Bundle	Maximum probability of occurrence (training set)
F1	0.99
F2	0.40
F3	0.14
G1	1.00
G2	0.90
G3	0.85
G4	0.97
G5	1.00

3.8 Summary

The bundle approach developed in Chapter 2 was applied to the area of Edinburgh located within the by-pass, using data zones as spatial units. The choice of this geographical scope was driven by the larger scope of the study in terms of strategic vs site-specific decision-making and by discussions with the city's Parks & Greenspace service.

Natural spaces have the capacity to address issues linked to extreme weather events, environmental pollution, unhealthy urban lifestyles, emission of greenhouse gases and biodiversity loss. Nine ES were found to contribute to the prevention and / or mitigation of these issues, based on a literature review and inputs from the city's Parks & Greenspace service. The provision of most of these services lead to local benefits - in other words, they contribute to the well-being of those located in the vicinity of the natural features which provide them.

The selected services were quantified using publicly-available spatial data from recognised sources; the relationship between this data and the selected ES was determined by reviewing empirical studies. The resulting models were implemented in Python scripts, which were run in ArcGIS Pro to generate a dataset of ES values by data zone.

The identification of ES Bundles shows that the nine ES are distributed into four ES Bundles - a qualitative interpretation of the PCA axes suggests the influence of soil sealing and tree cover in the consistent associations found among the services. The identification of Spatial Bundles show spatial patterns of multiple benefits: the 558 data zones of the study area are clustered into eight bundles which show different levels of ES provision across the city. Three bundles are characterised by their capacity to enable food growing, while the remaining five bundles consist in a gradient of simultaneous provision of all but two services. A majority of data zones belongs to the two lowest bundles in the five-level gradient of ES provision.

Regression analyses on the spatial bundles categorisation confirms the role of soil sealing and tree cover as drivers for their formation. It appears that tree cover plays a more preeminent role than soil sealing in predicting bundle assignation: for instance, obtaining a bundle outcome characteristic of a relatively high ES provision mainly depends on having a tree cover higher than around 13%, while a very low ES provision of ES can only occur in data zones where tree fractions are lower than around 7%.

The outcomes of this Chapter, both in terms of bundle results and process of implementation, are discussed in Chapter 6 to identify potential uses for bundle approaches. The next Chapters (4 and 5) inform this discussion by studying the integration of the ES concept in decision-making at city scale.

Chapter 4

Methodological framework for exploring the integration of ecosystem services in decision-making

4.1 Introduction

Exploring the research question of this thesis, "How could knowledge derived from ES bundle assessments be effectively used in decision-making related to land-use planning and management?", led me first to develop and implement a bundle approach in the City of Edinburgh (Chapters 2 and 3). As described in Chapter 1, the potential contribution of bundles to decision-making relies on what they can evidence, as well as their salience, credibility and legitimacy (see Chapter 6), but also on the decision-making context itself. The capacity of governance systems and institutions to provide the necessary level of leadership, infrastructure, skills, legal framework, and incentives, would play an important role in the success of a bundle approach. In particular, the extent to which the ES concept is already integrated into decision-making, can be expected to influence whether and how a bundle approach could be beneficial.

This Chapter describes the methodology used in this thesis to investigate the integration the ES concept in strategic decision-making at city level. Section 4.2 first unpacks the meaning of "integration" into three main dimensions, providing a structure upon which to base the analysis. The following sections describe the multi-method approach adopted to explore these dimensions: content analysis of strategical documents (section 4.3) and interviews with key informants (section 4.4).

4.2 Methodological approach: opening the "integration" box

Analysing the integration of the ES concept in strategic decision-making requires defining precisely what is meant by the term “integration”. Across the literature exploring the “inclusion” (Cortinovis & Geneletti 2018), “governance attention” (Frantzeskaki & Tilie 2014), “(discursive) representation” (Hansen et al. 2015, Nordin et al. 2017), “recognition” (Kabisch 2015, Piwowarczyk et al. 2013), “incorporation” (Lam & Conway 2018) and “uptake” (Rall et al. 2015) of the ES concept in decision-making, one can identify three main dimensions of ES integration, detailed thereafter:

1. Awareness of the ES concept;
2. Understanding of the ES concept; and
3. Attention to ES in policies, high-level action plans and decision-making processes.

First, the ES concept can be explicitly included in strategic decision-making, e.g. through explicit references in planning documents or in the discourse of high level decision-makers: using Rall et al. (2015) terminology, this component will be referred to as *Awareness of the ES concept*.

Nevertheless, there are many instances reported in the literature where the concept's presence is implicit: again using Rall et al. (2015) terminology, this component will be referred to as *Understanding of the ES concept*. In this study, two levels of understanding are considered. The first level involves a recognition of the relationships between people and nature, as evidenced by the use of general terms such as “benefits”, “values” or “contribution”, or by a discourse linking nature with human well-being (including aspects such as health or economic security). The second level relates to a deeper understanding of the ES concept, as evidenced by a discourse linking ES (mentioned implicitly or explicitly) and elements either influencing them or being influenced by them. Such elements were identified using the IPBES conceptual framework, which provides a simplified model of interactions between people and the rest of the fabric of life on Earth (Díaz et al. 2015). It includes six interlinked components operating at various scales in time and space: nature; ES; a good quality of life; anthropogenic assets; direct drivers of change; institutions, governance systems and other indirect drivers of change (Figure 4.1). The first three components were described in section 1.2.1. Anthropogenic assets refer to knowledge, technology, work, financial assets, built infrastructure that, together with nature, are essential in the co-production of ES. Direct drivers are external factors which affect nature directly in a physical sense, positively or negatively: examples include habitat conversion, climate change or species introduction. Indirect drivers include economic, demographic, institutional or governance related factors which are the root causes of direct drivers: although the "Indirect drivers" component is not used to analyse the understanding of the ES concept, it is partly addressed in the third dimension of integration as described below.

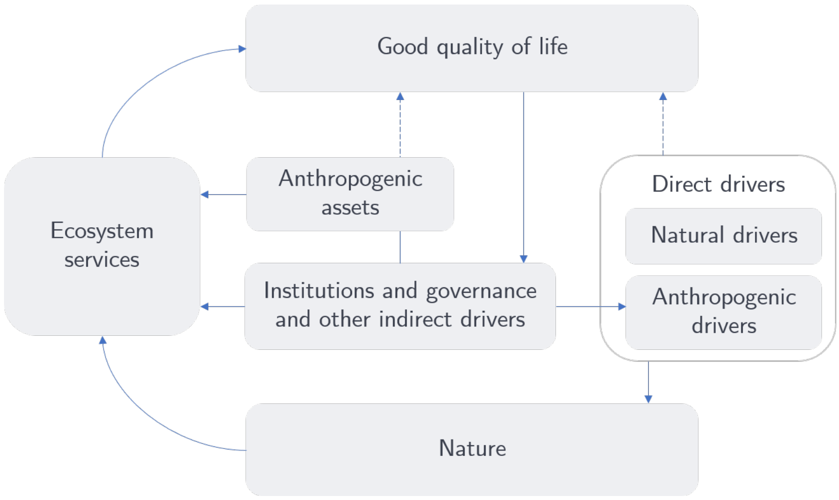

Figure 4.1: The six interlinked components of the IPBES conceptual framework, which are used in this chapter to structure the analysis of the understanding of the ES concept. Modified from Díaz et al. (2015) to reflect the terminology adopted in the thesis

The third dimension of integration of ES relates to how they are effectively leveraged to achieve policy objectives. This aspect can be reflected by the attention given to ES in policies and high-level action plans (e.g. Cortinovis & Geneletti (2018)), as well as the processes directing the relationships among different sectors in city government, and between city government and external partners (e.g. Frantzeskaki & Tilie (2014)). In this Chapter, I am referring to this dimension as *"Attention to ES in policies, high-level action plans and decision-making processes"*. This dimension allows the partial coverage of the component of the IPBES framework relative to governance systems. A full analysis would require an in-depth study of the governance processes in the City of Edinburgh, including the link with higher level policies and legislation.

The chapter views decision-making as encompassing formal, published strategies and action plans (referred hereafter as 'strategic documents'), as well as the perceptions and opinions of decision-makers responsible for delivering them. Therefore, a multi-method approach was developed to investigate the three dimensions of ES integration introduced above. It involves content analysis of strategic documents and interviews with key informants: the methodology for these two aspects is detailed in the next section.

4.3 Content analysis of strategic documents

4.3.1 Research questions

The three dimensions of ES integration were explored using quantitative and qualitative content analysis, built around the following research questions:

Table 4.1: Research questions derived from the dimensions of ES integration

Dimension	Research questions for content analysis
Awareness of the ES concept	1. Are ecosystem services referred to explicitly? In which context(s)?
Understanding of the ES concept	First level: 2. Which terms are used to refer to ecosystem services (implicitly)? 3. Which specific ecosystem services are referred to? 4. Are individual ecosystem services mentioned together? Second level: 5. To what extent are the links between nature and ecosystem services represented? 6. To what extent are the links between ecosystem services and quality of human life represented? 7. To what extent are the links between ecosystem services and anthropogenic assets represented? 8. Which direct drivers and their impact on nature / ecosystem services are mentioned?
Attention to ES in policies, high-level actions and decision-making processes	9. What types of ES-related policies or high-level actions do the documents provide for? 10. To what extent do proposed policies or high-level actions target ecosystem services, their drivers or the linked anthropogenic assets?

To answer these research questions, I first identified relevant strategical documents across decision-making areas of interest (subsections 4.3.2 and 4.3.3). Then, I analysed their content by assigning any relevant piece of text to categories derived from the research questions (a process known as “coding” and described in section 4.3.4). Some of these categories were pre-defined while other were identified inductively, making the approach a hybrid between quantitative and qualitative analysis (Bryman 2016). Finally, I generated quantitative summaries of the coding results and discussed them to provide answers to the research questions (subsection 4.3.5).

4.3.2 Scope in terms of decision-making areas

Studying the integration of ES in decision-making is only relevant in areas concerned with the outcomes to which (semi-)natural areas can contribute. Therefore, I only considered decision-making areas – thereafter called "sectors" – which relate to the well-being and sustainability issues identified in Chapter 3, sections 3.3.1 and 3.3.2:

- Extreme weather events
- Environmental pollution
- Lifestyles characterised by sedentarism, unhealthy diets and stress
- Greenhouse gases emissions
- Lack / Loss of biodiversity

Based on these issues and on decision-making areas considered in previous work, as referenced in sections 1.4.2.2 and 4.2, the following sectors were included:

- **Planning** is concerned with the general direction of spatial development, which makes it relevant to all issues above.
- **Greenspace** is concerned with the planning and management of greenspaces to improve residents’ health and well-being, and to mitigate pollution and climate change impacts.
- **Biodiversity** is directly addressing biodiversity issues, but contributes also to

the other sectors

- **Climate** is concerned with the prevention and mitigation of climate change, including in links with extreme weather events and greenhouse gases emissions.
- **Sustainability** includes general and overarching directions relating to environmental issues, including pollution and climate concerns.
- **Health** is concerned with safeguarding and improving the physical and mental health of urban residents, including when it comes to sedentarism, unhealthy diets, stress, and exposure to pollution.

The link between these generic sectors and the actual departments at the City of Edinburgh are provided in section 5.2.

4.3.3 Identification of relevant material

I sought to collect City-level strategical documents falling into at least one of the sectors identified in the previous section. Strategies operating at a higher level than the Council were not included. Furthermore, only documents relevant to the year of analysis (2019) were considered.

A desk search on the City Council web pages was conducted to identify relevant documents:

- The core website (https://www.edinburgh.gov.uk/);
- The Open Data portal (https://data.edinburghopendata.info/dataset); and
- The repository of Committee documents (https://democracy.edinburgh.gov.uk/).

A preliminary list of documents identified from these sources was completed after a review with the Manager of the City's Parks & Greenspace service. The full list is provided in Table 5.1 (section 5.2 in Chapter 5). As highlighted by Cortinovis & Geneletti (2018) and Lam & Conway (2018), strategic documents can typically be divided into two parts:

- A first part containing descriptive text which provides background and rationale for the policies or high-level actions provisioned by the documents (Lam & Conway 2018): following Cortinovis & Geneletti (2018), I am calling this part the "information base"; and
- A second part detailing the policies or high-level actions: I am calling this part 'statements of policy and strategy' (denomination modified from Lam & Conway (2018)).

Three of the documents listed in Table 5.1 did not fall into this typical structure:

- The Edinburgh Design Guidance only contains an information base, with the corresponding statements of policy and strategy being listed in the Local Development Plan.
- The information base and statements of strategy for climate change adaption have been separated into two distinct documents: the Edinburgh Adapts Vision and the Edinburgh Adapts Action Plan.

The identified documents were analysed using a methodology known as coding and detailed in the next section.

4.3.4 Coding

The coding process enables the researcher to structure and analyse textual data by assigning pieces of information to different categories. In content analysis, categories are usually defined *a priori* for each aspects of interest to the study, as defined based on existing knowledge about the issue. Although I adopted this approach here, the list of categories was completed inductively by reading through a sample of three documents: the Local Biodiversity Action Plan (LBAP), the Open Space Strategy (OSS) and the Local Development Plan (LDP) (see Table 5.1, section 5.2, for a full list of the documents). The LBAP and the OSS were screened first, and any new category identified therein was added to the list. I then checked that no other new categories emerged from the analysis of the LDP. These three documents were selected for their relevance to the subject: it was assumed that if saturation was reached with these documents, then it was not likely that any relevant category would be missed.

Nine aspects of interest were defined based on the research questions:

- I. ES: Terminology;
- II. ES: Individual Services;
- III. Nature: Terminology;
- IV. Nature: (Semi-)natural features;
- V. Good quality of life;
- VI. Anthropogenic assets;
- VII. Direct drivers;
- VIII. Policies & high-level actions: Targeted components;
- IX. Policies & high-level actions: Types of measures

Content from the information bases were coded using categories under aspects I to VII, while the statements of policy or strategy were coded under aspects VIII and IX. This distinction in coding was not used in previous studies - the rationale for doing it here relies on two reasons:

- I have aspects of interest directly pertaining to statements of policy or strategy (VIII and IX), which are therefore relevant to investigate solely using this part of the documents. Because studying the types of high-level actions related to ES was not an objective of previous studies, distinguishing between document parts was not relevant for them.

- Aspects I to VII appear in both the information base and statements of policy or strategy. However, statements of policy or strategy are derived from the information base, such that occurrences in the latter can be expected to be closely linked to occurrences in the former: a high correlation was indeed found in an analysis of 22 planning documents conducted by Cortinovis & Geneletti (2018). Therefore, I considered that study of information bases only would provide an accurate measure of ES representation while avoiding double counting of the same issues.

Figure 4.2 below lists the coding categories determined for each dimension and constitutes the "coding manual" of the analysis (Bryman 2016). It also includes instructions for attributing pieces of text to each category.

I. Ecosystem services: Terminology

The code "Ecosystem services" is assigned when the exact term appears. The other codes are assigned when the term or one of its derivatives appears in the sense of ecosystem services

I.1. Ecosystem services
I.2. Contribution
I.3. Benefit
I.4 Value
I.5. Phrases linking nature to well-being

II. Ecosystem Services: Individual Services

Codes are assigned when a term or phrase describing the service appears

II.1. Air purification
II.2. Carbon storage / sequestration
II.3. Cooling
II.4. Noise attenuation
II.5. Water purification
II.6. Flood protection / mitigation
II.7. Habitat provision
II.8. Pollination
II.9. Food
II.10. Supporting identity
II.11. Recreation
II.12. Socialising
II.13. Experiencing nature
II.14. Education
II.15. Physical activity
II.16. Disservices

III. Nature: Terminology

Codes are assigned when the exact term appears (derivatives are accepted for biodiversity).

III.1. Biodiversity
III.2. Greenspace
III.3. Green / blue infrastructure or network
III.4. Natural environment or place
III.5. Natural capital
III.6. Ecosystem

IV. Nature: (Semi-)natural features

Codes are assigned either when the exact term appears, or a term that refer to a similar feature, in relation with ecosystem services.

IV.1. Trees / Woodland
IV.2. Soil / Geodiversity
IV.3. Private Gardens
IV.4. Water features
IV.5. Parks
IV.6. Allotment
IV.7. Brownfield

V. Good quality of life

Codes are assigned when the term appears, or a term referring to a similar aspect, in relation with ecosystem services

V.1. Health
V.2. Wellbeing
V.3. Sense of place
V.4. Economy
V.5. Energy

VI. Anthropogenic assets

Codes are assigned when the term appears, or a term referring to the same or a similar asset, in relation with ecosystem services

VI.1. Built environment
VI.2. Knowledge
VI.3. Financial resources

VII. Direct drivers

Codes are assigned when the term appears, or a term referring to a similar phenomenon, in relation with ecosystem services

VII.1. Climate change
VII.2. Pollution
VII.3. Exploitation
VII.4. Habitat conversion
VII.5. Invasive species
VII.6. Disease

VIII. Policies & high-level strategical actions: Targeted components

Codes are assigned to a policy or an action relating to ecosystem services. If it is directed towards their protection or enhancement, then the "Ecosystem services" category is used. If it targets anthropogenic and/or direct drivers, then the corresponding category is selected.

VIII.1. Ecosystem services
VIII.2. Anthropogenic assets
VIII.3. Direct drivers

IX. Policies & high-level actions: Types of measures

Codes are assigned to a policy or an action relating to ecosystem services depending on their type. The description of each type is provided in section xxx.

IX.1. Managing landscape features
IX.2. Building stakeholders' capacity
IX.3. Fostering collaboration
IX.4. Producing or using science

Figure 4.2: Coding categories used in the content analysis.

Coding was conducted using the software NVivo v12. Coding results were reported in an Excel file following a template hereafter called the "coding schedule" and reproduced in Appendix E.1 (Bryman 2016, Wilkinson et al. 2013). The schedule consists in a set of tables reporting quantitative data (number of references) as well as qualitative information (example of quotes). The schedule was populated for each sector: if a sector has more than one strategical document, coding results were merged.

4.3.5 Analysis

I performed quantitative and qualitative analysis of the coding results for the three dimensions of ES integration (see section 4.2):

- Awareness of the ES concept;
- Understanding of the ES concept; and
- Attention to ES in policies, high-level actions and decision-making processes.

The following sub-sections describe the methodology for each of them.

4.3.5.1 Awareness of the ES concept

This dimension relates to the explicit representation of ES in the documents. It was analysed with regards to code I.1. Two axes of analysis are of interest:

- The extent to which ES are explicitly mentioned across all documents; and
- The differences of explicit representation between sectors (cross-sector comparison)

Metrics were chosen following practices in the literature:

- For the first axis I used the frequency of occurrence of code I.1. across all documents (Lam & Conway 2018), compared with the frequency of all terms referring to the concept (codes I.1. to I.5)

- For the second axis, I used the presence or absence of code I.1. in each sector (Cortinovis & Geneletti 2018, Nordin et al. 2017).

The quantitative results were complemented with qualitative data on the context in which the explicit mentions appear.

4.3.5.2 Understanding of the ES concept

The analysis of the understanding of the ES concept was broken into three parts, detailed below:

- Implicit representation of the ES concept;
- Representation of individual services and multiple benefits;
- Representation of ES in link with nature, a good quality of life, anthropogenic assets and direct drivers.

a. Implicit representation of the ES concept

The implicit representation of the ES concept was analysed with regards to the occurrence of codes I.2 to I.5, the frequency of which have been recorded at the coding stage. Two axes of analysis are of interest:

- The types of implicit representation of ES, across all sectors; and
- The differences of implicit representation between sectors (cross-sector comparison).

As suggested by Bauler & Pipart (2013) and Mascarenhas et al. (2015), cited in Lam & Conway (2018), the number of mentions of the ES concept is one indication of the level of conceptual adoption. Using frequency-based metrics, following the approach taken by Lam & Conway (2018), would therefore be a relevant method to address my two axes of analysis.

However, it is crucial to note that most studies do not use the frequency of implicit terms to analyse the presence of the ES concept, but rather record the presence / absence of implicit mentions in documents (Nordin et al. 2017, Cortinovis & Geneletti 2018, Hansen et al. 2015, Wilkinson et al. 2013). As one author explains, the interpretation of frequencies would be made difficult by "the different lengths, writing styles, and foci of interest" of relevant documents (Wilkinson et al. 2013).

Yet, the "presence / absence" approach also presents flaws with regards to my objectives of analysis. Indeed, it does not differentiate between terms which may be anecdotally mentioned and those which may infuse whole discourses: as a result, I would not be able to gain detailed insight into the types of implicit representation appearing in the selected documents. This limitation did not present itself to previous investigators, as they did not seek to unpack the different language elements relative to the implicit representation of the ES concept. In that sense, the different writing styles and foci of interest, seen as barriers by Wilkinson et al. (2013), are here part of the object of study: what does the frequency of mentions of different terms tell us in terms of the language used when talking about ES? What does it tell us in terms of the focus on ES?

The frequency-based metrics chosen to address the two axes of analysis are the following:

- Analysis of the types of implicit representation across all sectors: comparing the total frequency of occurrences of codes I.2 to I.5 across the body of documents. The barrier mentioned by Wilkinson regarding different document length does not come into play here are there is no comparison between documents involved. Metric used: frequencies of term occurrence

- Analysis of the differences of implicit representation between sectors: the use of the "raw" frequencies of occurrence is prevented by the different document length across sectors, as highlighted by Wilkinson. Indeed, conducting a cross-comparison of sectors with this metric would be misleading: if document A has a background section of half the size of document B's, a term with an identical frequency for both would be an indication of a higher, not similar, use of this term to represented the ES concept in A compared to B. As a result, I needed a metric which would remove the dependence to the documents' lengths: I used the density of occurrence of each term within each sector, defined as the frequency of occurrence divided by the number of pages across all background sections within one sector.

Metric used: density of term occurrence in each sector

These quantitative results were complemented with qualitative data on the context in which the implicit mentions appear.

b. Representation of individual services and multiple benefits

The representation of individual services was analysed with regards to the occurrence of codes II.1 to II.16, the frequency of which have been recorded at the coding stage. Three axes of analysis are of interest here:

- The level of inclusion of individual services across all sectors;
- The differences of foci in terms of individual services between sectors (cross-sector comparison); and
- The extent to which multiple individual services are mentioned together across all sectors, and which ones.

Following the same approach as described for the implicit representation of the ES concept, the metrics used for the first two axes are:

- Frequencies of occurrence of terms or phrases relative to individual services across all documents; and
- Density of occurrence of terms or phrases relative to individual services, in each

sector.

To the best of my knowledge, the third axis of analysis has not been addressed in previous literature. I chose as a metric the frequencies of cross-mentions of individual services across sectors, as an indicator of the simultaneous mentions of two or more services.

It is worth noting that across all axes of analysis, no distinction was made between implicit or explicit mentions of individual services. These quantitative results were complemented with qualitative data on the context in which the mentions to individual services and multiple benefits appear.

c. Representation of ES in link with nature, a good quality of life, anthropogenic assets and direct drivers

The representation of ES, in link with the other components of the IPBES conceptual framework, was analysed with regards to the occurrence of codes III.1 to VII.6. Two axes of analysis are of interest here:

- The extent to which nature, a good quality of life, anthropogenic assets and direct drivers are referenced in link with ES, across sectors; and
- The differences of representations, between sectors, of the links between ES and the IPBES components (cross-sector comparison).

Relevant metrics were identified in the same way as the previous analyses:

- Frequencies of mentions of each component in relation to ES, across all documents; and
- Density of mentions of each component in relation to ES, in each sector.

These quantitative results were complemented with qualitative data on the context in which ES appear in link with nature, a good quality of life, anthropogenic assets and direct drivers.

4.3.5.3 Attention to ES in policies, high-level actions and decision-making processes

This part of the analysis focuses on the policy and high-level actions sections of the selected documents. Based on codes VIII.1. to IX.4., the analysis was conducted along three axes:

- The extent to which different types of ES-related measures are included across all documents;
- The differences of inclusion of ES-related measures between sectors (cross-sector comparison);
- The coherence between the level of inclusion of ES-related measures and the level of ES representation, across sectors.

Relevant metrics were identified in the same way as the previous analyses, with the analysis across sectors using frequencies of occurrences and the cross-sector comparisons using density of occurrences.

These quantitative results were complemented with qualitative data.

4.3.6 Quality of the methodology

No standardised quality criteria exist specifically for content analysis. Therefore, I am presenting here a short quality analysis based on the reliability and validity criteria, widely used in social research (Bryman 2016).

In the context of this study, assessing reliability means exploring whether the integration of ES in decision-making was investigated in a replicable manner. The attention given to the coding process gives confidence in the reliability of the methodology:

- The categories defined in the coding manual are mutually exclusive, so that the researcher is clear on which code to attribute to the piece of text under consideration;

- The categories are exhaustive thanks to the piloting process, which allowed to complete the preliminary list developed a priori based on previous knowledge; and
- The coding manual contains instructions on how to code the contents of the documents, so that researchers have no discretion in how to allocate the codes.

When it comes to validity, the question is whether the methodology actually allows to gain information on the integration of the ES concept:

- The selection of documents was made to reflect the decision-making areas of interest and were validated with the Manager of the City's Parks & Greenspace service. I am therefore confident that they provide a satisfactory coverage of the relevant decision-making context and policies.
- The use of frequency-based metrics in the analysis is expected to reflect the level of conceptual adoption of the ES concept (Mascarenhas et al. 2015).
- The issue of comparing frequencies in documents of different sizes has been circumvented by standardising frequencies with regards to the number of pages.

I am however aware that different approaches could have been taken. In particular, a simpler way to analyse the coding results would have been to avoid the use of frequency-based metrics and rely instead on the presence / absence of relevant terms, as done in previous studies - with the limitations outlined earlier in this section.

4.4 Interviewing key informants

4.4.1 Strategy: why interviews?

The analysis of strategical documents, described in the previous section, plays an important part in understanding the level of integration of the ES concept in decision-making. However, such an analysis is not able to give us information or access to meanings and choices in the decision-making process (Duke 2002, Winchester 1996): these aspects are indeed rooted in the experiences and perceptions of actors engaged in this process. In order to get a deeper understanding of the integration of the ES concept, I decided to draw on the perspectives of selected city government staff. My goal was to get insight into:

- What they saw as nature's contributions to people;
- How they perceived these contributions in the context of the policies they are involved in delivering; and
- How they viewed and used the ES terminology.

To achieve this goal, a qualitative approach offers crucial advantages. Compared to quantitative methods such as questionnaires, a qualitative approach makes it possible for the participants to explain the complexities of their perceptions and experiences; allows the participants to raise issues the interviewer may not have anticipated; and reduces the risk of forcing complex issues into preconceived categories (Valentine 2005). Furthermore, adopting a qualitative approach stresses the importance of understanding and recognising the viewpoint and position of those being studied (Duke 2002).

The most relevant strategy for the study was to rely on interviews with key informants. I chose to conduct individual interviews as opposed to group discussions (group interviews or focus groups) because my focus was on participants' individual perceptions and experiences, rather than on "how people respond to each other's views and build up a view out of the interaction that takes place within [a] group" (Bryman 2016).

The next sub-sections detail the specific methods used for sampling participants, collecting and analysing data, and dealing with ethical issues. The last subsection elaborates on the quality of the overall methodology.

4.4.2 Sampling participants

Interviewing aimed at gathering the perceptions of senior staff involved in delivering policies or high-level actions with a link to ES. The focus on senior staff, in contrast to more junior positions, was to ensure the strategic side of decision-making was captured. Emphasis was also put on the coverage of different sectors within the Council, to gain knowledge on a diversity of perceptions. Similar to Kabisch (2015), Rall et al. (2015), I aimed to secure a set of around ten such informants.

It is often difficult to identify and access senior government staff (Mikecz 2012, Lancaster 2017). The use of a snowball method can ease the process, as it can be assumed that senior people in a given field "are interconnected: that members know each other, either personally or by reputation, so that if you ask them who the key people in the field are, they will know" (Farquharson 2005). First, I identified participants thanks to the Manager of the Parks & Greenspace service, with whom I was already in regular contact and who knew the study and its objectives. I reached out by email mentioning that *"I would like to interview a few people across the different 'departments' of the City administration to understand how people in different departments perceive ES (or whichever terminology they may use to refer to benefits from nature) and what drives or limit their inclusion in the strategies / action plans they design. [...] I was wondering whether you had any knowledge on who may be relevant in other departments than yours to participate in this consultation"*. He suggested 11 potential informants who, after a first contact by email, either accepted to participate to the study or redirected me towards colleagues. This process ran from December 2019 to January 2020 and led to a final list of ten participants holding senior positions in the Council (Table 1). Because the participants covered all the decision-making areas identified in section 4.3.2 of this Chapter (Planning, Greenspace, Biodiversity, Climate, Sustainability, Health), I did not look for further snowball starting points.

Data collection was initially planned for the months of March and April 2020. However, disruption caused by the Covid-19 pandemic during these months meant that five participants had to drop out from the study. In the end, the study included five participants (Table 4.2), for which data collection stretched to July 2020. This covered all the relevant sectors, except for the health remit for which in the circumstances it was impossible to arrange coverage, despite multiple attempts to secure the participant's involvement.

More generally, uncertainties with the duration of the pandemic and the resulting lack of availability of relevant informants meant that recruitment of additional people in time for data to be analysed before the end of the study was a challenge and, ultimately unlikely to be achieved. For this reason, no further recruitment of participants was conducted.

Table 4.2: Number of participants pre- and post-Covid disruption, by Council service affiliation and for each relevant sector as defined in section 4.3.2. The Council service structure is detailed in Chapter 5, section 5.2, where their correspondence with the ES-relevant sectors is also explained.

Council service *Directorate: Section (remit, if relevant)*	Expected number of participants before Covid-19	Final number of participants	Main ES-related sectors
Place: None (executive position)	2	1 [a]	Planning, Sustainability
Place: Planning & Development (biodiversity)	1	1	Biodiversity
Place: Planning & Development (housing)	1	0	Planning
Place: Planning & Development (general)	1	0	Planning
Place: Parks & Greenspace	1	1	Greenspace
Place: Roads, Transport & Network (floods infrastructure)	1	1	Planning
Chief Executive's Office: Policy & Insight (climate)	1	1	Climate
Chief Executive's Office: Policy & Insight (sustainability)	1	0	Sustainability
Health & Social Care Edinburgh Integration Joint Board [b]	1	0	Health
Total	*10*	*5*	

[a] The interview could not be completed due to an emergency on the participant side. No suitable later date could be identified to finish the interview.

[b] The EIJB is a separate and distinct legal entity from the City of Edinburgh Council, responsible for decision-making around health. It is made up of representatives from the Council, NHS Lothian, Third Sector representatives, service users and carers.

Four of the five interviews could be fully conducted, covering all the aspects of interest (see next section), and lasted from 33 minutes to 51 minutes. One interview could not be completed: parts 3 and 4 of the interview guide could not be addressed (see next section). It lasted 21 minutes.

4.4.3 Data collection

The specific interviewing strategy needed to have a strong structure in order for all topics to be systematically covered, and to facilitate analysis according to categories determined in the content analysis part of the study. It meant having an interview schedule with questions addressing the different aspects mentioned above. At the same time, data collection needed to be flexible and adapt to participants' answers- for instance by changing the order of questions or asking additional ones to get more insight when necessary.

This *semi-structured interviewing* strategy was piloted at Dundee City Council in January 2020 with four senior members of staff, which allowed to develop the final interview schedule, presented in Appendix E.2. The pilot phase allowed me to use more specific language in the questions, and to identify a point in the interview where summing up the participants' previous responses would improve their understanding of the following questions. It also allowed me to get some experience navigating the challenges of power relations arising from interviewing so-called 'elite' participants – i.e. 'individuals or groups who ostensibly have closer proximity to power or particular professional expertise' (Morris 2009, Lancaster 2017). I found that the people who were the closest to the subject were used to talk about it in a certain way, and that I would sometimes need to probe a bit deeper to get answers to my questions (Mikecz 2012). I also realised that my position as a student was both advantageous and disadvantageous. The participants seemed happy to help me with my studies, especially because we had a connection through the person who helped me get in contact with them. I sensed they felt 'non-threatened' and were talking openly. Nevertheless, my status as a student probably increased the tendency of participants to get into a 'lecture' on the subject, as mentioned above. This tendency may also have been reinforced by my perceived young age (the participants who asked about my background were often surprised to learn that I had a 4-year working experience between my MSc and my doctoral studies). In the end, the interview schedule contained five parts:

- Part 1 focuses on the respondent's role and responsibilities within City government, in order to provide context to their answers and to set the ground for Part 2.

- Part 2 enquires about the respondent's perception of nature's benefits in relation to their role and responsibilities as described in Part 1. Language used in the questions do not include the term "ecosystem service(s)" to avoid leading the respondents.

- Parts 3 and 4 are dedicated to the explicit discussion of the ES concept – Part 3 is addressed to respondents who are familiar with the concept and Part 4 to the others

Face-to-face enquiry was initially preferred to online interaction, as there is some evidence to suggest that the quality of data derived from telephone interviews is inferior to that of comparable face-to-face interviews (Bryman 2016), in particular because participants are less likely to be fully engaged with the process. Face-to-face interviews were conducted for the first two interviews, but social distancing measures implemented in Scotland from mid-March 2020 required the use of online calls for the remaining three interviews.

4.4.4 Data analysis

All interviews were recorded and transcribed. Notes were also taken during the interviews.

Data analysis involved coding the transcripts to uncover themes in the perceptions of participants and to organise information according to the three dimensions of ES integration identified in section 4.2. This process is consistent with the thematic analysis methodology, as described by Douglas (2002), where "the general issues that are of interest are determined prior to the analysis, [but] the specific nature of the categories and themes to be explored are not predetermined".

Theme identification techniques reported by Ryan & Bernard (2003) were used to conduct the analysis. More specifically, I looked for repetitions, metaphors and analogies, transitions, and linguistic connectors.

The analysis was conducted in NVivo 12.

4.4.5 Ethical considerations

The main ethical challenge was to ensure the participants' confidentiality. The study involved a small sampling frame due to the narrow focus of the investigation, so that specific care was needed to ensure participants would not be identifiable (Lancaster 2017). First, I was aware that reporting the participants' job titles and professional backgrounds could reveal their identity, even though these descriptors would be valuable for the analysis. As a result, although I recorded these items, I did not report them in the thesis, and informed the participants I would not in any other publications either. I identified the participants using solely the decision-making area and Council department to which they belonged. Still, the policy area was narrow enough that even mentioning the remit of the participant (e.g. climate or biodiversity) could lead to their being identified. To mitigate that risk, I ensured I focused on cross-sector findings, as much as was possible without omitting key results from the interviews.

I made sure participants were fully informed on the nature of the research and its implication from the outset, by sending them an Information Sheet and a Consent Form (Bryman 2016), based on templates provided by the University for ethical approvals. The participants were also given the opportunity to ask any questions at the start of the interview. The Information Sheet and the Consent Form are available in Appendix E.3.

Interviews were recorded and the recordings immediately transferred to a secure folder on my personal laptop. Transcription was performed by TP Transcription, a UK GDPR-accredited firm also registered with the Information Commissioner's Office in the UK, and holding Cyber Essentials and ISO27001 accreditation. Recordings and transcription files were shared using UK-based servers and protected by passwords.

Transcription files and the NVivo project file generated to analyse data were stored in the same secure folder as the recordings.

Ethical clearance was provided by the University of Dundee School of Social Sciences Research Ethics Committee under approval number SREC – UOD-SoSS-GEO-PG-2019-056.

4.4.6 Quality of the methodology

The concepts of reliability and validity have been established as important criteria in assessing the quality of quantitative research. However, their applicability to qualitative studies has been questioned, with concerns around whether they still bear meaning in a qualitative context (Rolfe 2006, Bryman 2016). While some view that they can be directly applied to the case of qualitative research with only a few adjustments (e.g. Mason (1996)), others have advocated "[the substitution of] new terms for words such as validity and reliability to reflect interpretivist [qualitative] conceptions" (Seale

1999). They argue that the quality of a study in each paradigm should be judged by its own paradigm's terms (Healy & Perry 2000, Lincoln & Guba 1985).

The latter is the view I am taking to assess the quality of the interview methodology. Although there is no accepted consensus about the standards by which qualitative research should be judged, the concept of trustworthiness, established by Lincoln & Guba (1985), is helpful in justifying the quality of the methodology proposed in this section. The trustworthiness of a methodology depends on four criteria: credibility, transferability, dependability and confirmability (Lincoln & Guba 1985).

- *Credibility* is concerned with the consideration of multiple possible accounts of social reality, through the implementation of adequate methods and the validation of collected data.
  - Participants sampling: emphasis was put on covering different departments of city government to gain knowledge on a diversity of perceptions; however, a fuller picture could have been achieved by including non-governmental organisations jointly participating in decision-making. The impact of Covid-19 also meant that the initial coverage was compromised and one interview shortened. It is with these limitations in mind that the interviews outcomes should be interpreted.
  - Data collection: By using semi-structured interviews, I enabled participants to expand on their perceptions, which were then triangulated with information from the documents. This process contributed to ensure the credibility of the methodology.
- *Transferability* refers to the presence of enough contextual elements for other researchers to conclude on the relevance of results for their work. In this study, I gathered contextual information in two ways:
  - The interview schedule included several questions on the respondents' role

and responsibilities, as well as the governance context in which they operate.

  – The document analysis also provides extensive data on the policy and legal framework surrounding the delivery of ES in the case city.

- *Dependability* can be viewed as the qualitative equivalent of reliability. It is concerned with whether another investigator would have generated similar data and induced similar interpretations from the set of collected data. The nature of social reality makes it impossible to exactly replicate any interview, however the fact that the schedule was piloted gives confidence in the dependability of the data collection methodology. Regarding data analysis, although no replication of coding was done in the study, the resulting code book is available and can be critically reviewed by peers.

- *Confirmability* pertains to the researcher's efforts in preventing their personal values or theoretical inclinations from influencing participants. I addressed this issue by ensuring not to use the term "ecosystem services" during the interview, until the part dedicated to an explicit discussion of the concept.

Although the quality of the methodology was impacted by the Covid-19 pandemic, the attention given to its trustworthiness, as described above, gives confidence in the results it generated.

4.5 Summary

This Chapter presents the methodology adopted in this thesis to analyse the integration of the ES concept in strategic decision-making. The planning, greenspace, biodiversity, climate, sustainability, and heath sectors are considered. The methodology is organised around three main dimensions of ES integration: awareness of the ES concept; understanding of the ES concept; and attention to ES in policies, high-level action plans and decision-making processes. These dimensions are explored with a multi-method approach consisting of a content analysis of strategical documents, and interviews with key informants.

The next Chapter (Chapter 5) reports results from the implementation, in the City of Edinburgh Council, of the methodology described here.

Chapter 5

Integration of the ES concept in the City of Edinburgh Council

5.1 Introduction

This Chapter investigates the integration of the ES concept across the services of the City of Edinburgh Council, then discusses it in relation to similar analyses in other locations. It contributes to addressing one of the thesis' aims, describing and discussing the current integration of the ES concept in high-level urban decision-making (see section 1.3), following the methodology developed in Chapter 4.

After this Introduction, section 5.2 describes the decision-making context around ES in the Council, with regards to governmental structure and breadth of strategical documents. Section 5.2 is followed by two sections reporting results from the content analysis of strategical documents (section 5.3), and from the interviews with key informants (section 5.4). These results are then synthesised and discussed to present a contextualised picture of the integration of the ES concept in the City of Edinburgh Council (section 5.5).

5.2 The decision-making context in the City of Edinburgh

This section identifies the parts of the Council's organisational structure which are relevant to ES, as determined from the collected documents and the interviews. The list of collected documents is then presented, classified according to the Council section responsible for it, and the generic sectors of decision-making identified in section 4.3.2 of Chapter 4. The interrelationships among the documents are then mapped to show the links between the different sectors.

The City of Edinburgh Council is divided into four directorates, two of which are relevant to ES: The Chief Executive's Office and Place. Directorates have several divisions, which are themselves organised in sections. Across the Chief Executive's Office and Place, four sections are of interest: Planning & Development (Place); Parks & Greenspaces (Place); Roads, Transport & Network (Place); and Policy & Insight (Chief Executive's Office). Strategic planning for health and social care is delegated to the Edinburgh Integration Joint Board, which is a separate and distinct legal entity from the Council. It is made up of representatives from City of Edinburgh Council and NHS Lothian, Third Sector representatives, service users and carers.

The responsibilities of the different offices are as follows:

- *Planning & Development* is responsible for the formulation and implementation of development policies and action plans relative to the use of land in the Edinburgh area. Its wide remit includes the following ES-related responsibilities: integrating standards set out by the Parks & Greenspace team, overseeing the building and maintenance of flood defences, and developing and implementing a biodiversity strategy.
- *Parks & Greenspace* is responsible for the formulation and implementation of

policies ensuring the continued protection and management of the city's public greenspaces. Their actions aim to ensure all city residents, workers and visitors have access to quality greenspace for a variety of purposes, including socialisation, physical activity, experiencing nature and growing food.

- *Roads, Transport & Network* is responsible for the formulation and implementation of policies dealing with transport-related infrastructure and planning. Its remit includes road maintenance and safety, public transport and parking, the management of flood defences and the development of an integrated and sustainable transport system. Notably, it develops and oversees actions aiming at increasing the levels of walking and cycling in Edinburgh (active travel). It also oversees responsibilities related to air quality, such as monitoring requirements.
- *Policy & Insight* is responsible for the City's overarching policies, including those related to sustainability and climate adaptation.

Some of the ES-related responsibilities described above are shared with other stakeholders in structures called Partnerships, which typically comprise the Council, key external public and private stakeholders across the city, the third sector and community groups. Partnerships are intended to enable joint working across the city on a number of cross-cutting issues such as sustainability and climate (Edinburgh Sustainable Development Partnership), biodiversity (Edinburgh Biodiversity Partnership) and greenspace (Edinburgh Living Landscape Partnership). Additionally, and as mentioned above, health strategies are developed by a dedicated Partnership which is distinct from the Council: *The Edinburgh Integration Joint Board (EIJB)* integrates the Council and health boards into one public body, as per the Public Bodies (Joint Working) Act 2014. In effect, the Council and NHS Lothian delegate to the EIJB resources and responsibility for planning health and social care functions. The EIJB is responsible for setting out the vision, intent and strategic priorities for health and social care in Edinburgh. It is supported by the Edinburgh Health and Social Care Partnership, which is the operational delivery mechanism for the EIJB and provides health and social care services across the city.

The ES-related policies and strategies developed by the Council and its Partnerships are listed in Table 5.1, which links them to the relevant Council's office and specifies the sector most closely related to them. Sectors are the decision-making areas defined *a priori* in Chapter 4, section 4.3.2. Although they do not fully match the Council's organisational divisions, a correspondence can easily be drawn from the scope of these strategical documents, where:

- Planning and Biodiversity are under the remit of the Planning & Development office;
- Greenspace coincides with the Parks & Greenspace office;
- Sustainability and Climate are under the remit of the Policy & Insight office, while flooding aspects are also of relevance to the Roads, Transport & Network office; and
- Health is covered by the Health & Social Care Integration Joint Board and, to a lesser extent, by the Roads, Transport & Network office (active travel remit).

Table 5.1: List of relevant strategic documents for the City of Edinburgh

Title	Date	Office	Sector
Local Development Plan	2016	Planning & Development	Planning
Edinburgh Design Guidance	2018	Planning & Development	Planning
Edinburgh Biodiversity Action Plan, 2019 - 2021	2019	Planning & Development	Biodiversity
Open Space Strategy 2021	2016	Parks & Greenspace	Greenspace
Trees in the City - Trees & Woodlands Action Plan	2014	Parks & Greenspace	Greenspace

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Title	Date	Office	Sector
'Cultivating Communities - A Growing Success': The 3rd Allotments Strategy for the City of Edinburgh, 2017 – 2027	2017	Parks & Greenspace	Greenspace
Edinburgh Living Landscape Programme Plan	2014	Parks & Greenspace	Greenspace
Resilient Edinburgh Climate Change Adaptation Framework 2014-2020	2013	Policy & Insight	Climate
Edinburgh Adapts Vision 2016 - 2020	2016	Policy & Insight	Climate

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Title	Date	Office	Sector
Edinburgh Adapts Action Plan 2016 - 2020	2016	Policy & Insight	Climate
Sustainable Edinburgh 2020	2016	Policy & Insight	Sustainability
Edinburgh's Sustainable Energy Action Plan 2015 – 2020	2015	Policy & Insight	Sustainability
Edible Edinburgh: A Sustainable Food City Plan 2014-2020	2014	Policy & Insight	Sustainability
Edinburgh Health and Social Care Partnership Draft Strategic Plan 2016 - 19	2015	Health & Social Care Integration Joint Board	Health

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Title	Date	Office	Sector
Edinburgh Integration Joint Board - Strategic Plan 2019-2022	2019	Health & Social Care Integration Joint Board	Health
Air Quality Action Plan, Progress with Actions 2015	2015	Roads, Transport & Networks	Health; Transport
Active Travel Action Plan, 2016 Refresh	2016	Roads, Transport & Networks	Health; Transport

It is worth noting that there is no City-level document related to flooding, as flood risks are managed at the scale of the Local Plan District in Scotland (Flood Risk Management (Scotland) Act 2009). These Districts were delineated based on river catchments and cross administrative and institutional boundaries: Edinburgh belongs to the Forth Estuary district, which includes 12 other local authorities. Because the scope of the study is restricted to City-level documents, the Forth Estuary Local Flood Risk Management Plan was not included in the analysis.

Furthermore, a preliminary screening of the documents showed that the Active Travel Action Plan and the Air Quality Action Plan did not actually contain any reference to ES; as a result, they were not analysed further, and the Transport sector was not considered in the analysis. It can also be concluded from this observation that the ES concept has not permeated decision-making in these areas.

The study of the rest of the documents showed that these were not independent from one another. Rather, direct and indirect links tie them together: they were found to support, influence, set requirements to, or be aligned with one another, as well as with higher level legislation and strategies (Figure 5.1).

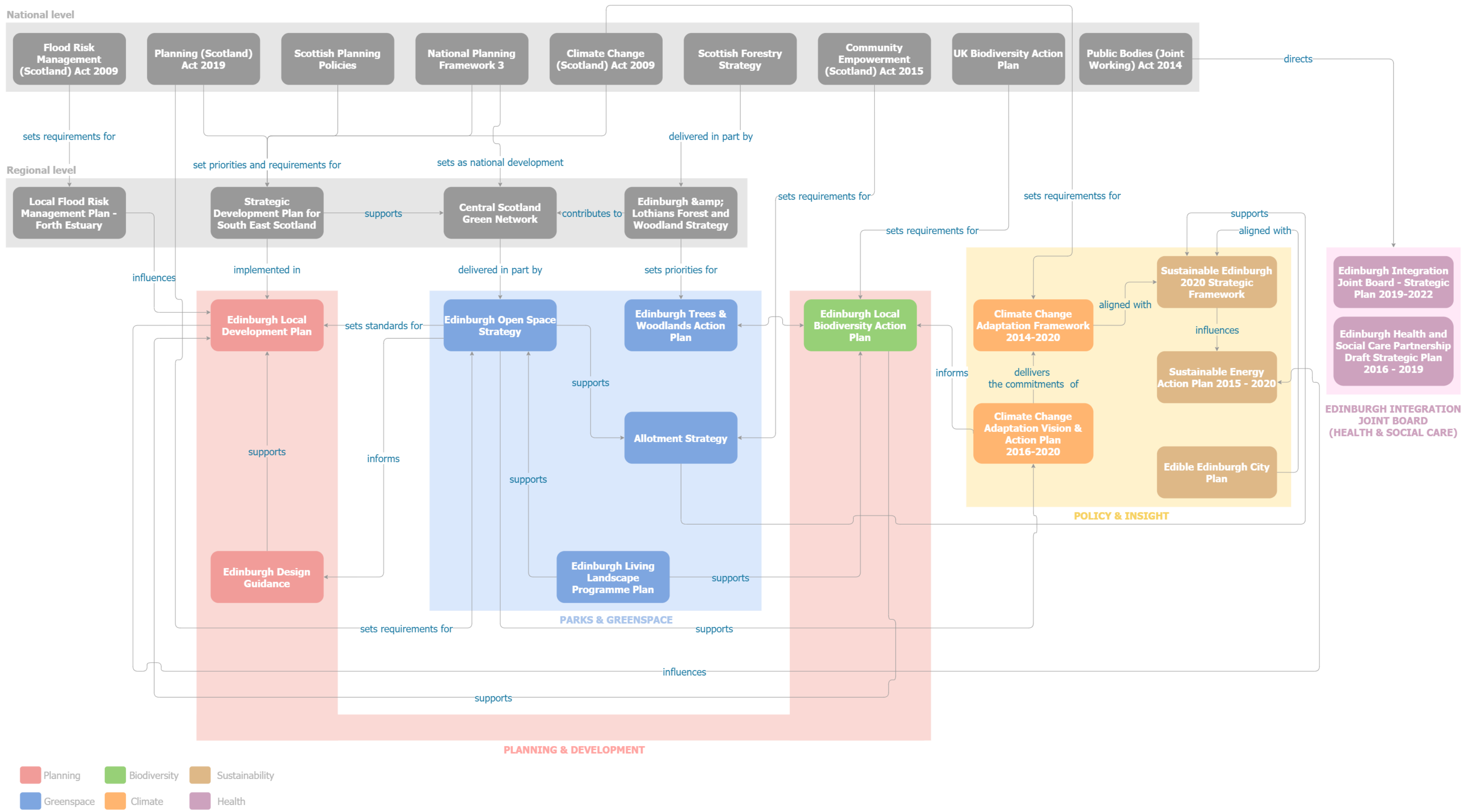

Figure 5.1: Mapping of City-level strategical frameworks and action plans, including links to regional and national policy and legislation. The documents are categorised by sector and are grouped according to the Edinburgh-specific offices.

5.3 Results from the content analysis of the City's strategical documents

5.3.1 Awareness of the ES concept

Rarely is the ES concept used explicitly in strategic documents. While it has been referenced over 100 times across all sectors (both explicitly and implicitly), only nine occurrences of the exact words "ecosystem service" or "service" were found, appearing in four sectors: biodiversity, greenspace, climate and planning.

The Local Biodiversity Action Plan (LBAP) uses the ES concept explicitly as part of its effort to show the importance of biodiversity and geodiversity for the City. It highlights the role of biodiversity and geodiversity in "underpinning" ES, mentioning for instance in its vision that "species-rich network of habitats [. . .] [form] a foundation for ecosystem services". Although the LBAP promotes the creation and maintenance of such networks, it also recognises that they can be a vector for the spread of invasive non-native species, the adverse effect of which is expressed partly in terms of "disrupt[ion] [of] ecosystem services". The LBAP is supported by two pieces of greenspace strategy, the Edinburgh Living Landscape (ELL) Programme Plan and the Trees and Woodlands Action plan. The ELL Programme Plan highlights in its rationale the importance of greenspace for the City's economy by using the term "ecosystem services" and explicitly referring to some of them individually. The Trees and Woodland Action Plan mentions the term in two different contexts: first in its introduction to the benefits of trees of the City, by singling out the removal of air pollutants as a "service", then when discussing the implementation of an ES valuation software. In this last instance, both the removal of air pollutants and the storage and sequestration of carbon is addressed. Trees are also the focus of the Edinburgh Design Guidance (EDG) when it comes to explicit reference to the ES concept: only in its section dedicated to trees and woodland, when highlighting their importance for well-being and the city's character, does the EDG uses the term "ecosystem services".

In none of the cases detailed above is the ES concept used to frame strategies or action plans. Rather, the term "ecosystem services" is used as an expression to describe the contribution of nature to the City, alongside other wording such as "benefits". It is worth noting that in some instances, ES are listed as benefits alongside expressions which could indeed be considered ES themselves: the EDG mentions that trees are "important for the quality and character of the landscape, [. . .] cultural heritage, ecosystem services" and the LBAP includes "ensuring climate change resilience" as a benefit of habitat networks alongside "forming a foundation for ecosystem services". The limited awareness of the ES concept in strategic documentation is even more apparent when noticing that its explicit representation does not extend to the main pieces of strategy for the greenspace and planning sectors, namely the Open Space Strategy and the Local Development Plan.

5.3.2 Understanding of the ES concept

The analysis of the understanding of the ES concept includes its implicit representation, the representation of individual services and multiple benefits, and the representation of ES in link with nature, a good quality of life, anthropogenic assets and direct drivers.

5.3.2.1 Implicit representation of the ES concept

The notion of relationship between people and nature appears in the reviewed documentation beyond explicit references to ES. Four different elements of language, implicitly referring to the ES concept, are used: phrases linking nature to well-being; benefits; contributions; and values.

'Phrases linking nature to well-being' refers to general expressions about the role played by nature, for instance highlighting that "trees are a key part of our armoury to combat climate change" or stating that "new greenspace provision should be informed by an understanding of local community needs, including health and wellbeing". Wording around the terms 'benefits' and 'contributions' is another general way of referring to the relationship between nature and people, for instance to suggest that "local greenspaces in new housing developments could deliver multiple benefits", to state the importance of "allotments [which] provide many benefits for plot holders and their families" or to stress that "trees and woodland [...] make a vital contribution to quality of life". Indicative of a more explicit approach to linking nature and people is the use of 'values' and its derivatives: for instance, citizens are said to "place great value on Edinburgh as a green city" and to "value daily contact with nature very highly", while community gardens are recognised for their "health and well-being value to local communities" and wooded environments for their "spiritual value".

When accounting for these implicit references, all sectors were found to feature some level of inclusion of the ES concept in their strategic documents (Figure 5.2). There is however a notable difference across sectors, where those most closely associated with managing landscape features –greenspace, biodiversity and planning – contain the highest frequency of terms. Among them, "benefits" and its derivatives emerge as the dominant elements of language linking people and nature: it is the most frequently used across all sectors, representing half of all references to the ES concept and appearing in four out of six sectors (Figure 5.3 and Figure 5.4). In contrast, explicit references to ES is the least frequent way of conceptualising these links. Furthermore, as shown in Figure 5.4, more than one type of representation can occur within a single sector: the most diverse mix of terminologies is found in planning, greenspace and biodiversity, with at least four types of representation co-existing in their strategic documentation (explicit and implicit). The other sectors use only one or two different elements of language – either benefits, contributions, or phrases linking nature to well-being. Values and ES, the most explicit terminologies conceptualising the link between people and nature, are not used in these sectors.

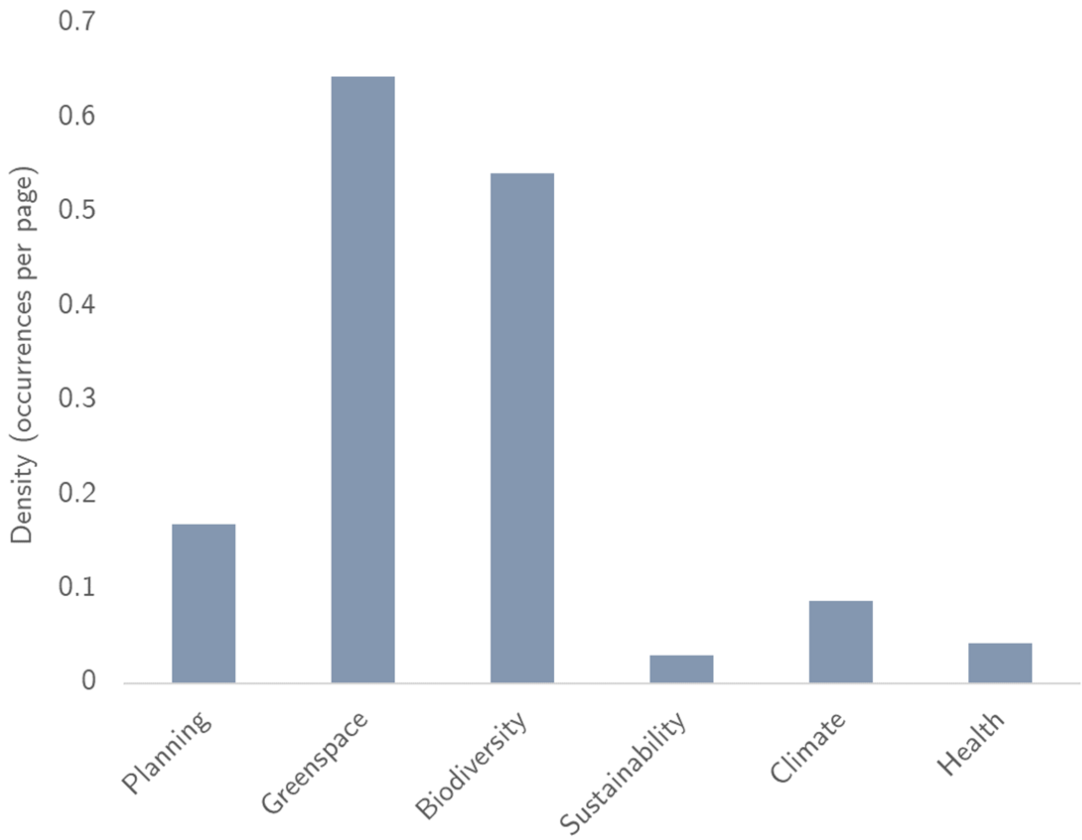

Figure 5.2: Density of representation of terms associated with the ES concept, broken down by sector of decision-making

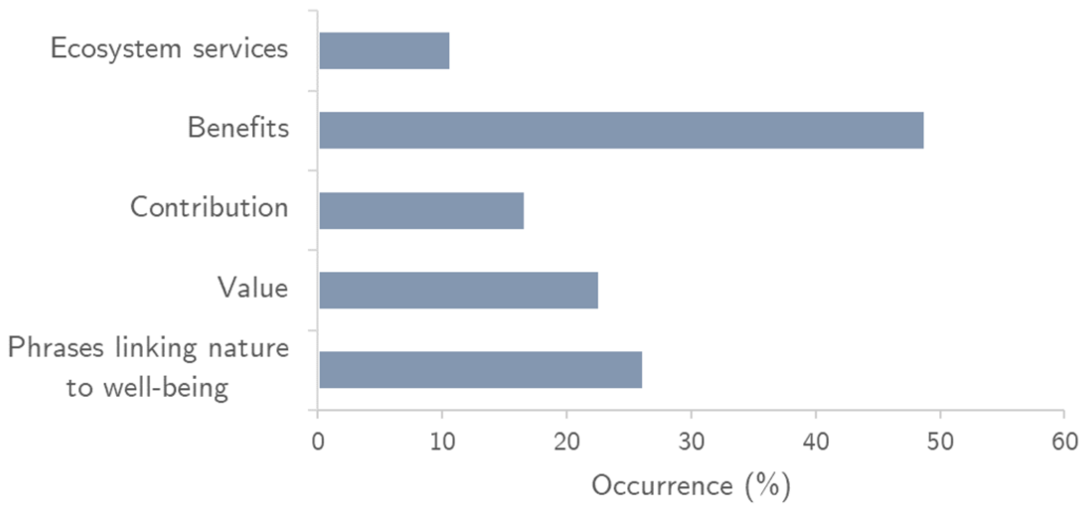

Figure 5.3: Occurrence of terms associated with the ES concept, measured in percentage of all mentions across reviewed documents

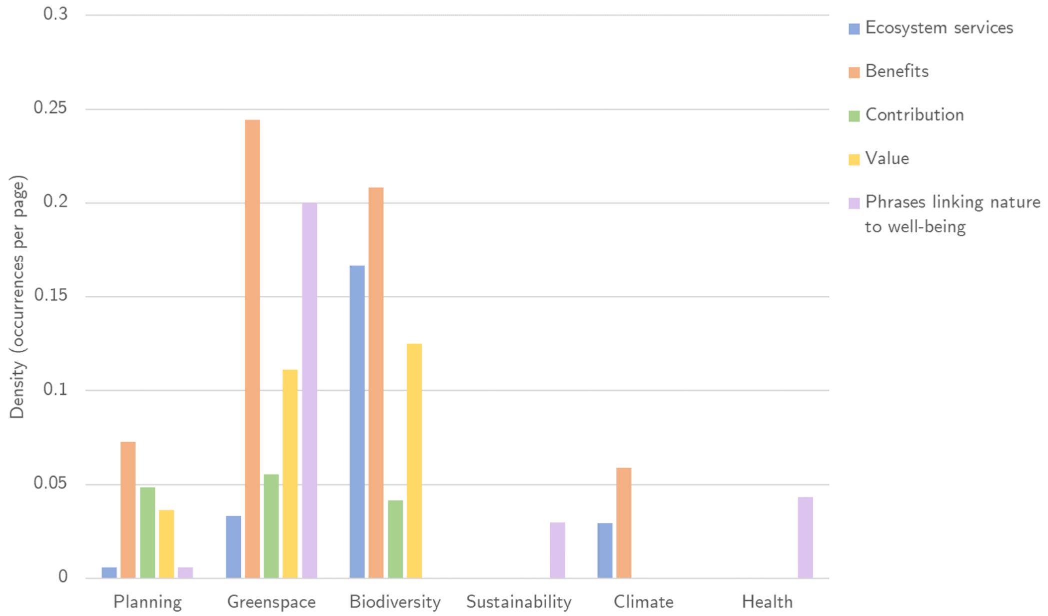

Figure 5.4: Density of representation of terms associated with the ES concept, broken down by sector and by type of term

Where the documents provide more detail on nature's role in well-being, they refer to specific benefits such as "holding water during heavy rainfall events", "storing carbon", "encourag[ing] children to play outside" or "strengthening communal activities". These mentions of specific benefits are seen as implicit references to individual services and more generally to the ES concept. They are found across the greenspace, biodiversity, planning and climate sectors (Figure 5.5), suggesting that these sectors hold, to a certain extent, an understanding of the specific ways that nature contributes to well-being. However, little to no such detailed references occur in the sustainability and health documentation, where the ES concept is mentioned using general phrases exclusively (Figure 5.4), therefore hinting at a low perception of the links between nature and people in these sectors.

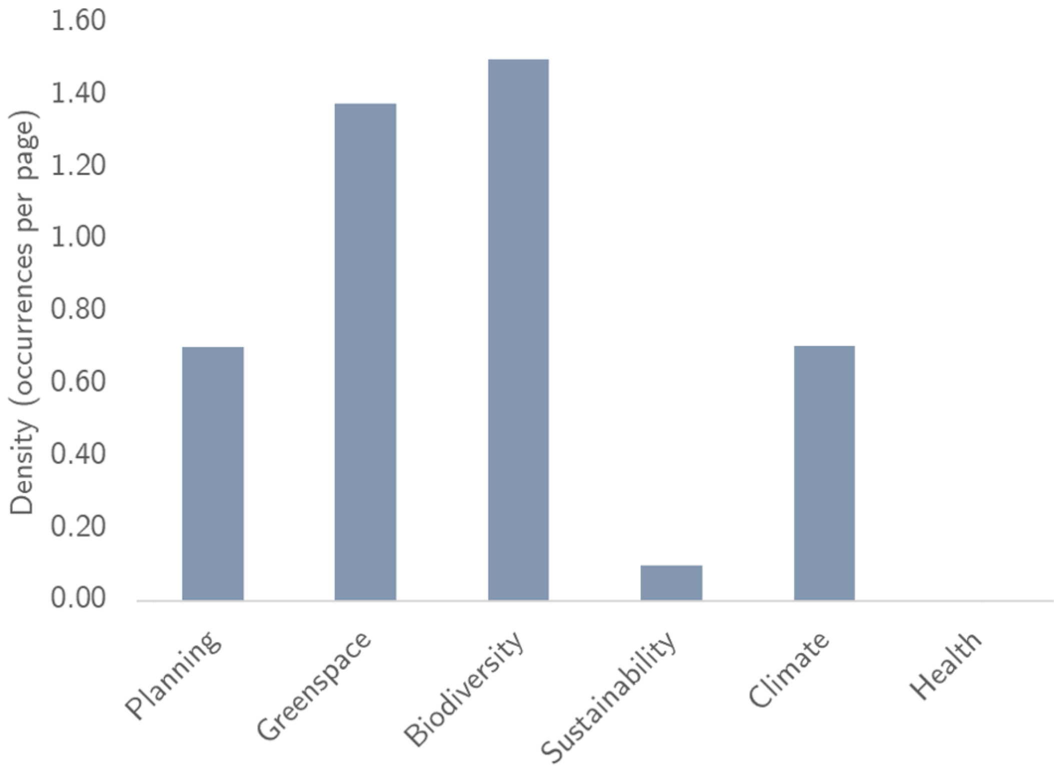

Figure 5.5: Density of representation of terms referring to individual ES, broken down by sector of decision-making

5.3.2.2 Representation of individual services and multiple benefits

The most frequently mentioned benefit of urban greenspace is the provision of habitat (Figure 5.6), referenced as a foundation for other services and therefore as an indirect contribution to well-being. For instance, the Open Space Strategy states that establishing "green networks [...] for wildlife [...] allow[s] people to experience nature as part of their daily lives" and the Edinburgh Design Guidance mentions the creation of wetland habitats in the context of developing surface water storage basins. The second most mentioned service is the production of food, either as a benefit of allotment gardening ("promoting healthier eating", "provid[ing] sustainable food at a low carbon cost") or as an argument for creating greenspace ("creating inspiring places for new communities to [...] grow food", "provid[ing] the opportunity [to] integrate orchard and allotment provision"). The remaining mentions are dominated by non-material services, with regulating services being the least cited. There is a notable exception in flood protection and mitigation, and to a certain extent water purification, which are frequently cited compared to other regulating services such as cooling or carbon storage. References to these two services in relation to sustainable urban drainage systems (SuDS) suggests that the integration of SuDS into wider policy and guidance may have driven, at least in part, awareness of the role of greenspace in regulating water quantity and quality.

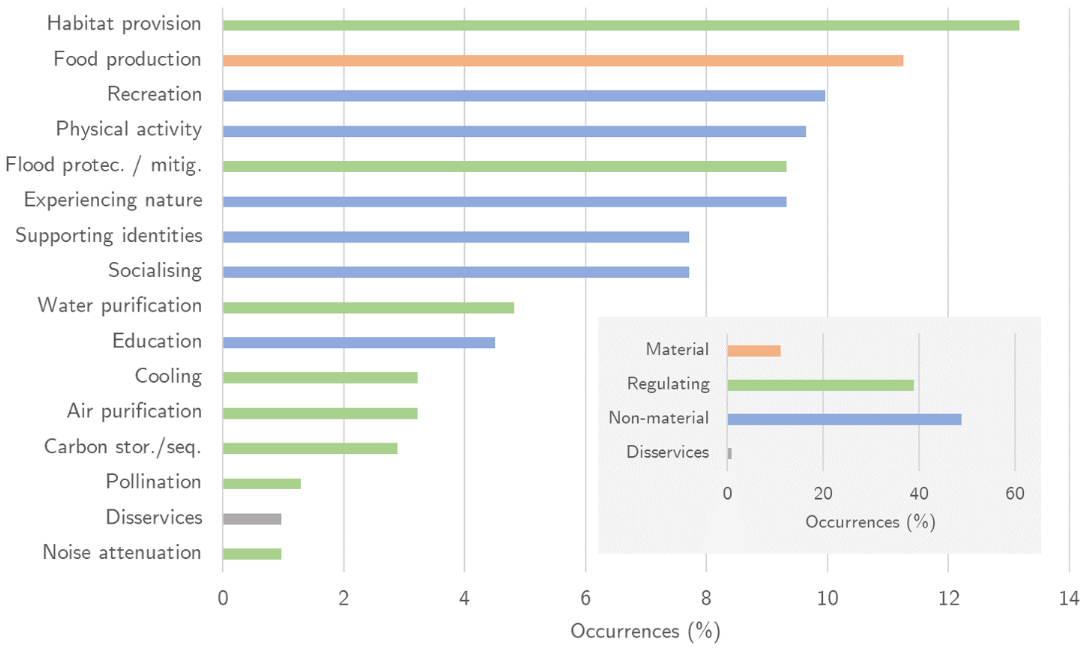

Figure 5.6: Occurrence of terms referring to individual services, measured in percentage of all mentions across reviewed documents. Insert: Occurrences of ES categories.

The study of the representation of individual services by sector (Figure 5.7) paints a slightly different picture to the cross-sector analysis presented above. Only in planning and biodiversity is habitat provision the most cited service, while food production holds a major presence in the sustainability and greenspace sectors only. However, the high amount of references to these two services in the sectors that mentions them the most, is enough to make them the most cited overall. More generally, the frequency of references to individual services differs across sectors. The planning documentation includes references to all individual services, and greenspace, biodiversity and climate also show a high coverage. In these last three sectors, there are references to regulating services at levels similar to some non-material services, therefore nuancing the overall finding that most regulating services are less cited than the non-material ones. In contrast to the high coverage reported above, the sustainability documentation refers to only a few services – food production, physical activity and socialising. A closer look shows that out of the three strategic documents identified for this sector, only the Edible Edinburgh Sustainable Food City Plan refers to specific benefits from nature. Given the Plan's scope, it is not surprising that the individual services associated with sustainability are delivered by allotments and other community growing spaces.

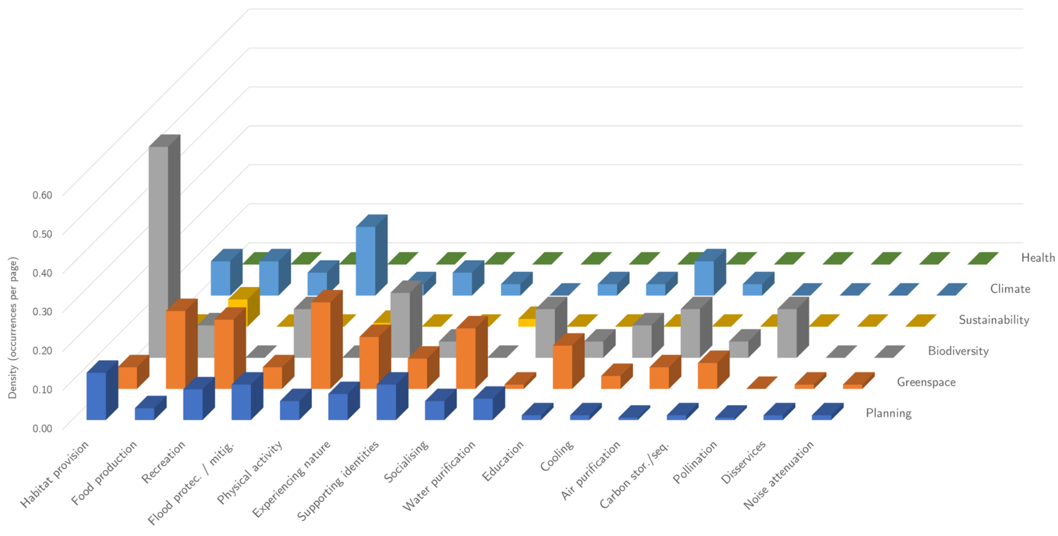

Figure 5.7: Density of representation of terms referring to individual services, broken down by sector

As mentioned above, more than one individual service can be found within a single sector. While references to many services can occur independently in different parts of a document, they can also appear together in the same piece of discourse. I refer to these joint references as mentions of "multiple benefits", which reflect an understanding that individual services can be delivered simultaneously, or more rarely "trade-offs", pointing out negative impacts of some services on others. Multiple benefits mainly appear among non-material services (Figure 5.8, bottom right), for instance when mentioning the role of parks as a "place to exercise and play informal ball games; walk the dog or go for a run; come together for local events; watch wildlife and scenery through the seasons; and experience natural open space". Reference to multiple benefits among regulating services also exist, albeit to a lesser extent and mainly relative to flood protection and mitigation (Figure 5.8, left side). For instance, the Climate Change Adaptation Action Plan mentions the role of greenspace in "provid[ing] areas for holding water during heavy rainfall events, while increasing tree cover supplies shade during warmer weather and draws pollutants from the air". In contrast with multiple benefits, there are few references to trade-offs. They appear in the Open Space Strategy, which highlights the need to ensure that the creation of new allotments "will not impact on the availability of greenspace for other recreational uses", and in the Edinburgh Design Guidance, which warns about shade-providing trees also blocking views from buildings.

	Air purification	Water purification	Carbon stor./seq.	Cooling	Flood protec. / mitig.	Noise attenuation	Pollination	Habitat provision	Recreation	Education	Experiencing nature	Socialising	Supporting identities	Physical activity	Food production	Disservices
Air purification	10															
Water purification	2	14														
Carbon stor. / seq.	3	2	9													
Cooling	**5**	1	2	10												
Flood prot. / mitig.	**6**	**14**	**6**	**6**	29											
Noise attenuation	2		1	1	2	3										
Pollination						0	4									
Habitat provision	2	3		1	**5**	1	1	41								
Recreation		1	1	1	3		1	**5**	31							
Education		1	1		1			1	**5**	14						
Experiencing nature	1	3	2	3	**5**	1	1	**6**	**7**	**5**	29					
Socialising								2	**7**	**6**	**6**	24				
Supporting identities	1							3	**5**	4	3	2	24			
Physical activity	2	2	1		4	1		3	**6**	**5**	**8**	**11**	2	30		
Food production		1	1	1	3		1	3	**5**	**5**	3	**10**	1	**9**	35	
Disservices				1			1		1		1					3

Figure 5.8: Total mentions and cross-mentions of individual ES. In bold and highlighted in orange are cross-mentions with occurrences in the fourth percentile.

5.3.2.3 Representation of ES in link with nature, a good quality of life, anthropogenic assets and direct drivers

The link between the ES concept and nature is obvious given the definition of ES. Nature is referenced alongside ES in almost all mentions to the ES concept (Figure 5.9), either using a general terminology such as "green infrastructure" or highlighting the role of specific (semi-)natural elements. General terminology, especially related to 'greenspace', is the most common; in contrast, ES are less frequently associated with the specific natural elements or spaces supporting them. The role of trees and woodland is particularly accentuated compared to other types of natural features or spaces, with statements such as "increasing tree cover supplies shade during warmer weather", "trees and woodland make an important contribution to the character and quality of the urban area" or that "the capacity of trees to attenuate water flow reduces the impact of heavy rain".

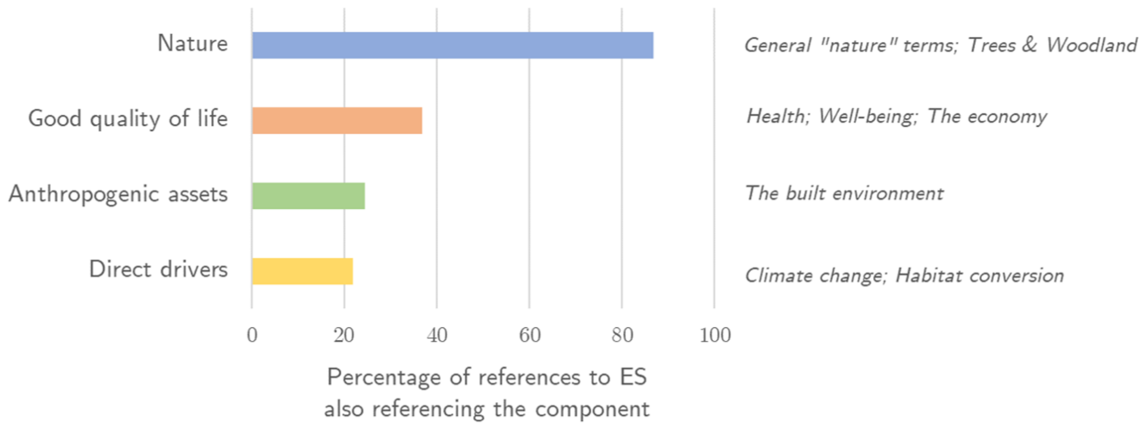

Figure 5.9: Amount of references to the ES concept in link with nature, a good quality of life, anthropogenic assets and direct drivers. Terms in italics are the most cited items within each of the four elements.

The link between ES and societal outcomes is also straightforward. Outcomes regarding well-being, health, sense of place, energy and the economy are connected to ES in just over a third of references to the ES concept (Figure 5.9). Health, well-being and the economy are the most frequently cited as benefiting from the provision of ES. For instance, the reviewed documentation recognises the role of "outdoor recreation [in] improv[ing] health and well-being" or the importance of "ground storage for flood waters [provided by greenspaces], [in] reducing the need for costly defences".

Anthropogenic assets and drivers of change, which are not directly part of the definition of ES, are less frequently mentioned (Figure 5.9). Anthropogenic assets, which help in delivering ES or mediating their impact on societal outcomes, are referenced alongside 20% of occurrences of the ES concept. Among assets investigated in this study, the built environment is the most featured: the reviewed documentation highlights the importance for new and existing development to integrate natural elements to "reduce the risk of flooding" and decrease "thermal gain", while providing habitat and enhancing the attractiveness of buildings. The role of the other anthropogenic assets mentioned in the documents, i.e. knowledge and financial resources, appear more rarely. Where drivers of change are mentioned, it is to highlight the role of ES in mitigating them. Strategic documents link "multiple benefits from greenspace" to "resilience to climate change" by identifying carbon storage and flood protection as key services for climate change adaptation. The documents also highlight how fighting against habitat conversion enhances the provision of a wide array of services including recreation, "local character" or "getting people more active". The links with other drivers such as pollution or the introduction of non-native species are less frequently discussed.

The results presented above allow the creation of an initial picture of how interlinkages between ES, nature, anthropogenic assets, a good quality of life and direct drivers of change, are represented in the City's strategical documents (Figure 5.10). Based on the IPBES conceptual framework, the figure shows that nature in general, but especially trees, are perceived to deliver ES which contribute to well-being, health and the economy. The built environment supports the delivery of ES, which also enhance new and existing development. They also play a role in mitigating the impacts of climate change, while benefiting from the fight against habitat conversion.

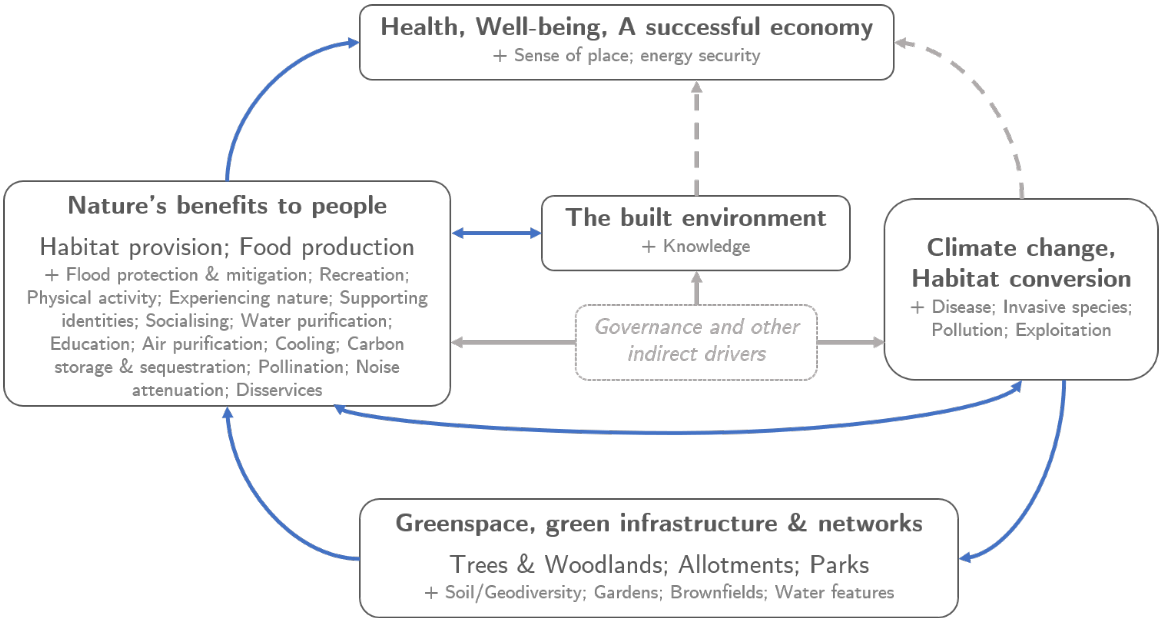

Figure 5.10: Representation of the interlinkages between ES, nature, anthropogenic assets, a good quality of life, and direct drivers of change. The blue arrows show the relationships between components. Grey arrows show links outside the scope of this study.

This overall picture summarised in Figure 5.10) is a good representation of the situation in planning, greenspace, biodiversity and climate, since these sectors include extensive links with all components, from nature to drivers (Figure 5.11). However,in sustainability and health, for which awareness and general understanding of the ES concept is the weakest (section 5.3.2.1), limited association is made with the other components of the framework.

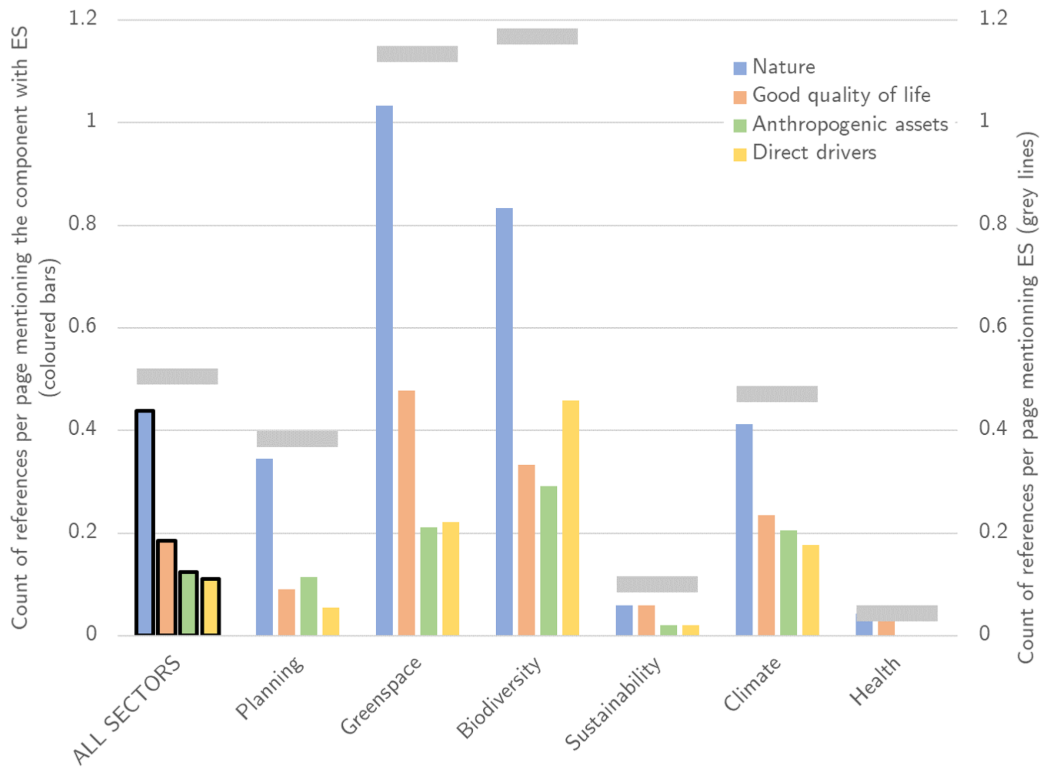

Figure 5.11: Relative amount of references to the ES concept in link with nature, a good quality of life, anthropogenic assets and direct drivers - broken down by sector.

The next section finalises the analysis by focusing on the attention given to ES in the document sections detailing the policies and strategical actions.

5.3.3 Attention to ES in strategical actions and decision-making processes

Policies and strategical actions are expected to influence the contribution of nature to society by addressing the delivery of ES, the interactions between them and anthropogenic assets and the effects of direct drivers such as climate change (Díaz et al. 2015). This section explores the attention given to ES by policies and strategical actions in the City. It involves trying to understand the extent to which ES-related measures appear in the portfolio of strategical instruments and what type of measures are included.

Unsurprisingly, the inclusion of ES-related measures in a specific sector depends on the extent to which its societal outcomes of interest directly rely on nature to be delivered. Greenspace, as a sector aiming to leverage naturalised spaces to increase the health and well-being of residents, has more than half its policies or strategical actions pertaining to the protection or enhancement of ES (Figure 5.12, blue bars). Some of these policies or actions are in fact statutory: greenspace standards set out in the Open Space Strategy, and which must be upheld in planning applications (Local Development Plan, Polices Env 17 to Env 20); the Trees and Woodlands Strategy makes it mandatory for the Council to effectively protect and maintain the ES trees provide (Policies 40 to 43); and allotment provision is governed by the Allotment Strategy (implementing the Community Empowerment (Scotland) Act 2015). It is worth noting that the Greenspace sector also exhibits some awareness and a high understanding of the ES concept in the background and vision part of its documents (Figure 5.12, orange dots). However, the level of awareness and understanding of the ES concept does not necessarily translate to a strong inclusion of ES-related policies or actions: the Biodiversity Action Plan, in the background of which the ES concept is well integrated, does however include a low proportion of ES-related actions compared to greenspace and food, which have a similar level of ES awareness and understanding. The actions of the Plan are indeed primarily directed towards the protection and enhancement of biodiversity for its own sake, and not necessarily as something from which people derive benefits. Similarly, planning, climate and health have wider scopes than the delivery of ES, and therefore show a comparatively low inclusion of ES-related policies or strategical actions.

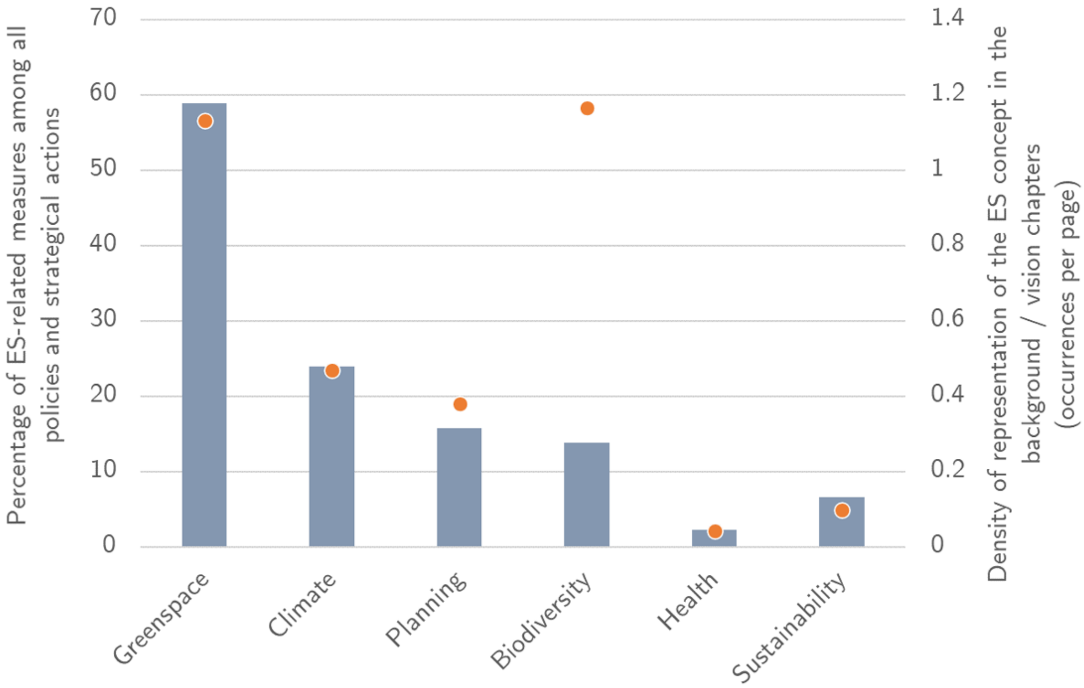

Figure 5.12: Relative amount of ES-related measures in the full breadth of policies and strategical actions in each sector (blue bars), represented against the density of representation of the ES concept in background and vision texts (orange dots).

Four types of policies and strategical actions have been identified across the documents: managing landscape features, building stakeholders' capacity, fostering collaboration, and producing and using scientific evidence (see Chapter 4).

5.3.3.1 Managing landscape features

The direct management of landscape features constitutes the majority of ES-related measures (Figure 5.13). They aim to increase ES delivery by enhancing the capacity of the landscape to provide them, through the improvement of natural land cover – for instance with planting schemes, requirements for new developments to implement SuDS, or suggestions to retrofit green infrastructure in existing developments –, the maintenance or restoration of ecosystem health – for instance by conducting conservation actions or removing invasive species –, and the design of greenspaces for leisure and physical activity purposes – for instance by incorporating unequipped play design, outdoor gyms, walking or running circuits.

5.3.3.2 Building stakeholders' capacity

In addition to acting directly on the urban environment, the City also seeks to build the capacity of its stakeholders to enable them to have more impact on the protection and enhancement of ES. Capacity building policies and strategical actions build on the recognition of the role of active citizenship in safeguarding and enhancing ES, as laid out in the background parts of some of the collected documents: the Open Space Strategy states that "improvements to Edinburgh's parks and greenspaces equally rely on active community involvement", while the Biodiversity Action Plan envisions that "people will be able to [..] directly contribut[e] through conservation action to protect and enhance [their local biodiversity]" and the Edinburgh Adapts Vision includes the public contribution to "an effective ecological monitoring scheme which allows swift action to protect nature from emerging threats".

Capacity building policies and strategical actions are of three types: raising awareness, training and mentoring, and providing incentives. Awareness raising pertains to the dissemination of information on the link between nature and well-being, on how to access nature's benefits (e.g. outdoor education or physical activity), and on the impact of climate change. It is directed towards the general public through websites or public information but also towards more specific stakeholders such as community groups. Some policies and actions go further by provisioning for training and mentoring land managers and community groups to undertake or participate to ES-positive projects such as habitat creation, environmental surveys, or food growing activities. The City also seeks to provide these stakeholders with additional incentives: the reviewed documentation includes general policies or objectives to "promote" and "encourage" ES-related actions, or more rarely specifies that funds will be made accessible.

5.3.3.3 Fostering collaboration

In addition to building the capacity of its stakeholders, the City also aims to foster collaboration for an optimised delivery of nature's benefits. To this end, it provisions for and encourages partnerships between itself and other entities: community groups such as Friends of Parks, public agencies such as NatureScot (formerly Scottish Natural Heritage), land managers and academic institutions. These partnerships are for instance expected to deliver naturalisation projects or to provide support to the City's efforts in environmental monitoring (see the Edinburgh Biodiversity Partnership), and sometimes include capacity building provisions.

5.3.3.4 Producing and/or using scientific knowledge

Finally, the City seeks to leverage its own expertise and its stakeholders' to produce and use scientific evidence in order to support the management of landscape features and to inform capacity building actions. It involves calling for the use of outputs from research projects, the launch of ES valuation exercises or planning for species surveys in priority areas. For instance, the Edinburgh Adapts action plan intends to "improve climate change resilience" through, *inter alia*, "mapping of the Council's green and blue estate, its connectivity and greenspace typology, including ecosystem services". The Biodiversity Action Plan includes the use of the mapping output from the John Muir Pollinator Way project in habitat creation site planning, as well as a measure to "continue a programme of volunteer, training, patrols and surveys for the Water of Leith to enable the monitoring of wildlife sightings, meadow surveys and river bank habitats".

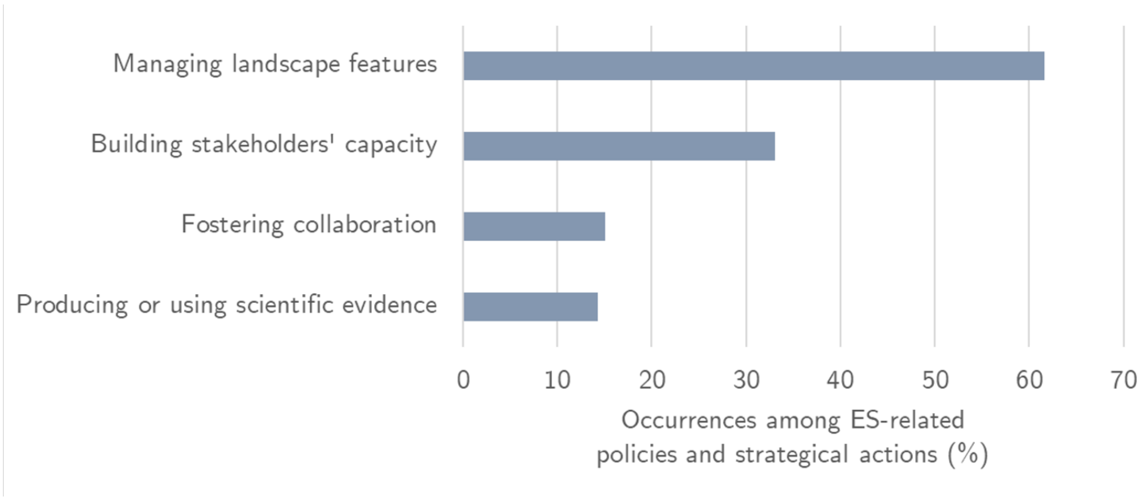

Figure 5.13: Relative amount of each type of ES-related policies and strategical actions

By providing insight into how ES are leveraged in policies and strategical actions, the analysis above refines the picture drawn in section 5.3.2 of the relationships between ES on the one hand, and natural and societal aspects on the other. A summary is provided below:

> *The council relies on nature, the built environment and its stakeholders in order to deliver ES and to address direct drivers. It directly manages landscape features using statutory measures or softer commitments, supported by the use of scientific evidence and the collaboration of other public bodies, academic institutions, community groups and land managers. It also seeks to build the capacity of its stakeholders by raising awareness on nature's benefits, providing training and mentoring opportunities, as well as incentives to act for the enhancement of ES.*

The study of the City's strategic instruments also provides us with some explanation regarding the various emphases identified and described in section 5.3.2. The natural features which are the most represented – trees, parks and allotments – are all elements for which statutory measures exist, as described earlier in this section. Similarly, the most mentioned ES – habitat provision and food production – are those whose protection and enhancement are the most subject to requirements. Statutory measures also support the role of the built environment in co-delivering ES, as well as protecting ES from potentially unsafe building practices, while they do not address the role of knowledge or financial resources in these regards. This may explain the heavier weight placed on the built environment in background sections, which is in strike contract with the central role played by stakeholders in policies and strategical actions.

5.4 Results from the interviews

5.4.1 Perceptions of the contributions of nature to society

The participants were prompted to share their understanding of the role urban nature plays in achieving their policy objectives. I found their discourse to include four different aspects: the way to which nature is referred when talking about its contributions; which environmental problems are seen to be addressed by nature; what the specific contributions of nature are; and the societal benefits to which they lead. Each aspect is described in the following subsections. A synthesis is set out at the end.

5.4.1.1 The way to which nature is referred

Before asking participants about the role urban nature plays in achieving their policy objectives, I explained the scope of the meaning of "urban nature". I made sure, to the extent possible, that they understood I did not restrict the scope to formal greenspaces and that I was looking for "anything you can think of that's green or blue in the city".

Participants reused the term "urban nature" in their responses, but also went on to use more specific terms to refer to the natural environment in link with its contributions to people, starting with "greenspace". In their discourse, greenspaces appear at times separate from the concept of urban nature – "it [urban nature] [. . .] *provid[es]* greenspace for recreation. . . ", "good quality greenspace *and* nature is hugely beneficial to people's physical and mental wellbeing. . . " while at times the terms seem interchangeable – "there's health benefits [to urban nature] [. . .] so we have standards about people should not be a certain distance away from accessing greenspace", "there is significant benefit in having good quality nature, or good quality greenspace in the city". Greenspaces are viewed as places "designed" specifically to enable people to be in nature – "passively" or "actively" –, but also more generally as natural places helping with mental health and adaptation to climate change.

Urban nature and greenspaces co-exist in participants' discourses with a diversity of terms that can be gathered under the "nature-based solutions" umbrella (NBS): the term itself is mentioned, along with "naturalised flood schemes", "green corridors", "green roofs", "green infrastructure", "trees" and "SuDS". I included these terms under the NBS umbrella either because the link was explicitly stated ("green roofs, green gardens, natural based solutions like that") or because there were in line with definitions of NBS currently used (for instance as seen in EU projects UNaLaB[1] or Urban GreenUP[2]). It is worth noting that participants tended to mention trees more often than other elements, for instance by reporting the "use [of] forests and woodlands to reduce flooding further down" or recognising the benefits "for the urban heat effect, [of] street trees". Interestingly, one participant voiced their concern about "planting trees to do carbon capture" at the expense of other solutions. To a lesser extent, water has also been singled out by some participants, in the forms of rivers, canals or ponds, for their role in flood alleviation or energy generation: "specific designs and infrastructure that's put in place to alleviate the flooding [. . .] like ponds", "rivers and running water produces hydropower". There is an important difference between NBS and greenspaces in the way their contributions are articulated in the participants' discourses. While greenspaces are viewed as *providing* amenity and non-

[1] https://unalab.eu/en

[2] https://www.urbangreenup.eu/

material contributions, participants view NBS in a role to help *reduce the impacts* of environmental problems associated with extreme events, climate change and pollution – for instance, they refer to “living roof[s] [...] [being] very effective at addressing the urban heat island”, to “trees and shrubbery help[ing] reduce particulate pollution” and “SuDS [as] specific designs and infrastructure that’s put in place to alleviate the flooding”. This suggests that participants perceive different types of natural spaces as associated with different types of contributions. These distinctions are further described in the following subsections.

5.4.1.2 The discourse around nature’s contributions

a. Nature helps to address the impacts of pollution and climate change.

All participants but one perceived urban nature and / or nature-based solutions as “important for”, “helping with” and “reducing” three main environmental issues: flooding, the UHI effect and air pollution. Carbon emissions were also mentioned, but to a lesser extent. The participant who did not mention these issues referred instead to the wider umbrella of “sustainability” and stressed the potential of the natural environment for energy production (“ground source heat”, “hydropower”, “tidal”).

Interestingly, the role of nature in addressing flooding, the UHI effect and pollution is not described in link with ecosystem functions – in other words, participants do not explicitly mention that nature retains water, cools the air, or captures air pollutants. The language they use clearly situates regulating services as a means to reduce harm to society, as opposed to them being the outcome of biophysical processes. They do not define them as being provided by specific places or natural components (except for trees) – in particular, regulating ES do not appear in participants’ discourses when they mention greenspaces.

b. Nature provides non-material services through greenspace

Across participants, it was possible to identify four main non-material services provided by greenspaces: recreation, gardening (food growing)[3] , the passive experience of nature ("just being out") and aesthetics ("the visual side", "a nice green city"). These contributions are specifically associated with greenspaces rather than nature in general or nature-based solutions. Furthermore, participants use the verb "provide" to refer to these services, anchoring them in the places that enable them to exist. They also systematically associated them with physical and mental health benefits – "mental health benefits of things such as gardening", "providing greenspace for recreation and for people to benefit passively from the natural environment [...] So, mental and physical health benefits." One participant also mentioned strengthened communities as an outcome, by pointing out through an example the sense of pride that communities can derive from their local greenspace ("people got very protective over it, very proud of it") and how that enabled them to deal with threats to it ("the demonstration of local community spirit ensured that [attacks on wildlife] never happened again"). There is therefore a contrast between the perception of regulating services on the one hand and non-material services on the other hand. Although participants link both types of contributions to desirable societal outcomes – better health, less pollution, adapting to climate change – for regulating services these outcomes are the lens through which they are defined, whereas non-material services are defined in relation to greenspaces. This reinforces the idea that greenspaces are considered as semi-natural spaces expected to deliver certain (non-material) benefits, rather than being a term synonymous with the natural environment.

c. Multiple benefits

It appears from the interviews that participants tend to think of nature's contributions as multiple benefits, either by speaking of "many benefits", "added benefits", "lots of ways", "various functions", "balance between [...]", or by using adverbs such as "also" or "as well".

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[3] Food growing is considered a non-material contribution here because emphasis is put on the mental health benefits of this activity rather than the fact that food is produced.

Some participants stressed the need to think of nature and the built environment as working together to bring these benefits. One participant spoke of the importance of putting “greening” “at the heart” of the current redesign of post-war council housing estates, while two others were more specific, mentioning the importance of “not only ensuring that there’s greenspace surrounding the development, but how that greenspace is designed is important” and giving the example of living roofs “that [bring] you many benefits to the energy efficiency and function of a building”. The link between nature and the built environment echoes the mention of nature-based solutions, of which “green infrastructure”, “green roofs” and “SuDS” are about the co-delivery of benefits by both the built and the natural environment.

One participant referred to multiple benefits in connection with trade-offs between the promotion of a specific contribution at the expense of others. As noted above in relation to the issue of promoting trees for carbon capture, of which the participant said “there’s so many other things that we can do”. The same participant also spoke of active travel, which was perceived as potentially accompanied by a removal of vegetation, leading to “losing the kind of multiple benefits of it”.

d. The intrinsic value of nature: biodiversity

Biodiversity is mentioned by participants when they are asked about the role of nature to achieve policy goals. It is perceived in most instances as an end goal, showing the intrinsic value placed on nature by participants: for example, one of them stated that nature “has the potential to provide biodiversity benefits” and another stressed that an additional benefit of having a “naturalised flood scheme” was to “[help] to increase biodiversity and protect natural places”. One participant perceived biodiversity as supporting the delivery of “ecological services”, by “do[ing] various functions”.

5.4.1.3 Perceptions of societal benefits from nature

Participants associate nature with four main societal benefits: adaptation to climate change; general health; mental health; and well-being. In their discourse, these benefits are either directly tied to nature ("it brings also a health and wellbeing benefit") or presented as associated to its contributions (" we find that food growing and being out helps with mental health"). Economic benefits are also mentioned to a lesser extent, either as a consequence of increased adaptation to climate change, or directly from being able to access food and recreation for free.

Three of the four main outcomes mentioned above relate to health, showing the importance attached by participants to the benefits of urban ES in this regard; an importance that has been, according to one participant, heightened by the Covid-19 pandemic. These three health-related outcomes are perceived as linked to greenspace and the non-material contributions it provides, as well as nature in general. They are however not mentioned in relation to nature-based solutions. In contrast, adaptation to climate change is linked to all types of urban natural environments – nature in general, greenspace and NBS. It is also associated with the capacity of nature to address floods, the UHI effect, carbon emissions and air pollution.

Perceptions of the role of nature and its benefits, as described throughout this section, can be synthesised with the following figure:

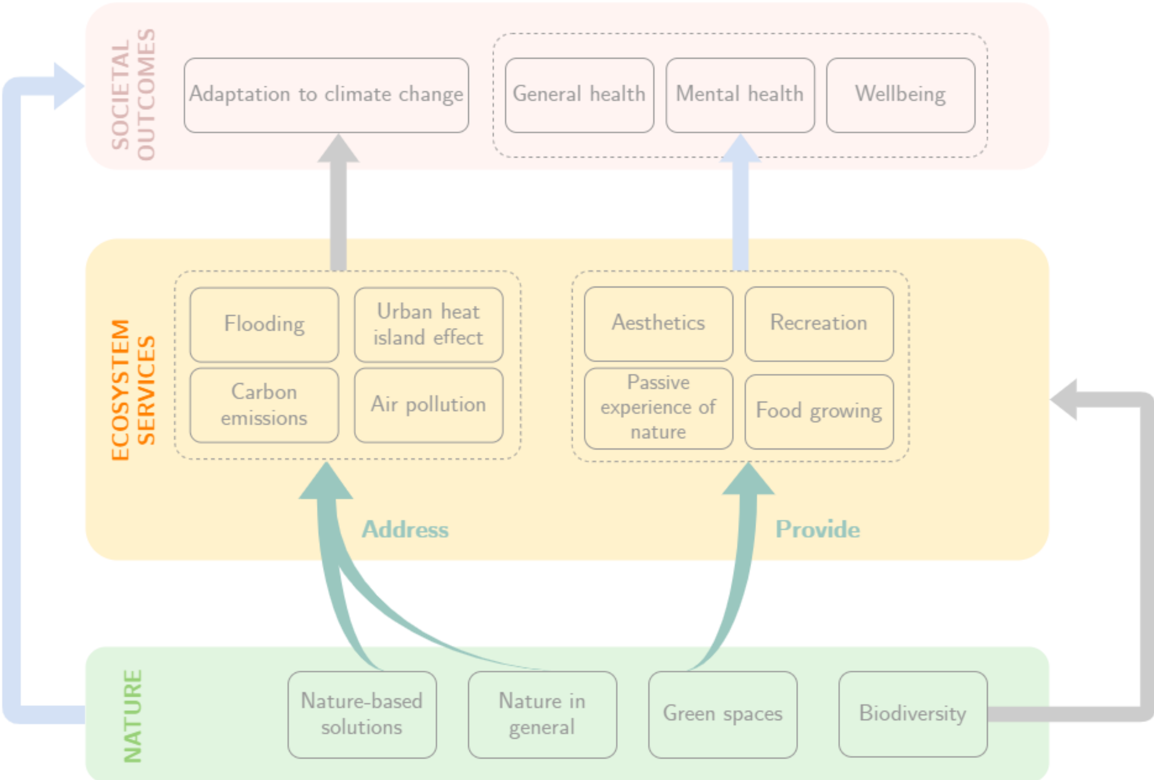

Figure 5.14: Perceptions of the role of nature and its benefits, as summarised across participants. Green arrows show the link made between nature and ES while blue arrows show the perceived relationships between societal outcomes and nature or ES. Grey arrows indicate links which are anecdotally mentioned.

5.4.2 Leveraging ecosystem services to achieve policy goals

5.4.2.1 ES valuation

Practices of "valuing nature", "measuring the value of our greenspace" or "assess[ing] the social benefits [. . .] of the city's greenspaces", were identified by some participants as crucial instruments in leveraging nature's contributions. Participants highlighted the importance of having data on the benefits of nature, measured in a way stressing its value to society, including aspects of health, well-being and adaptation to climate change. One participant mentioned that datasets on the health benefits of greenspace, as well as a social return on investment study, have been produced for this purpose. ES valuation is also seen as important in informing the directions of investment in greenspaces. One participant heavily stressed the need to "maximise the benefits" of actions taken towards the city's greenspaces, in a context of limited resources. For them, it meant ensuring that investment is directed towards actions enabling the provision of multiple benefits and / or towards areas of greater social need: the participant mentioned that measuring the multiple functions of different types of greenspaces, as well as using social measures, played a role in informing the directions of investment.

However they, along with other participants, stressed that valuation systems enabling them to make the case for greenspace when competing for resources with other areas of government, were still lacking. One participant said that individuals advocating for greenspace did not have access to the same level of information as those in different areas. To illustrate the issue, the participant talked of a situation where green roofs would have to compete with solar panels: they felt that the lack of data on green roofs' energy cost reduction would be detrimental to their business case. Participants stressed the need for guidance and contribution from experts in developing ES valuation methods, in particular standardised ones. More generally, the view was that demonstrating the value of the natural environment was crucial to leveraging its benefits for society, but that progress was needed to get suitable measures for these values.

5.4.2.2 Awareness-raising

Participants perceived the contributions of nature to society as poorly recognised within the Council. For instance, one participant mentioned "a real lack of awareness about a lot of these issues [nature's benefits] [by] colleagues that I work with" while another one recognised his own limited understanding of what nature's benefits were, saying "you might find engineers would probably, I wouldn't say we're ignorant of it, but [. . .]". Furthermore, lack of awareness was cited as a driver for the trade-off situations described above (tree planting and active travel, see section 5.4.1). Participants stressed the importance of awareness-raising to move towards a better integration of nature into high-level priorities (see section 5.4.2.4).

City-wide Partnerships around biodiversity and adaptation are viewed as important in raising awareness about nature's contributions. One participant stated "the role of the [Edinburgh Adapts] steering group [. . .] to raise awareness about adaptation", "to try and ensure that adaptations are embedded (sic), not only into other council areas and policies and plans, but to embed it in other organisations as well" while another talked about "influenc[ing] strategies and policies [. . .] definitely do[ing] it through the EBAP" [note: the Edinburgh Biodiversity Action Plan, developed and implemented by the Edinburgh Biodiversity Partnership]. The Edinburgh Adapts Partnership is also seen as a platform to impact high-level decision-making, with one participant explaining that "all those things operate at quite an officer level [. . .], they're all senior decision makers or politicians involved closely with those projects."

Awareness-raising efforts are also happening outside the scope of Partnerships. One participant mentioned they were "basically trying to educate people", while another said that other departments were "consulting with them". Furthermore, one participant mentioned a recently formed working group on green infrastructure, which they felt "has given [them] an opportunity now to have all this information fed up to the politicians".

According to participants, awareness about nature's benefits has been improving these last few years, not only due to individual and group efforts within the Council, but also to external factors. Two participants identified local and global campaigning – one talked about the "Greta Thunberg effect" – as instrumental in helping to raise awareness. One of them also mentioned local flood events as playing a role.

5.4.2.3 Collaborative work across departments and external organisations

For all participants, collaborations with colleagues and external partners appeared to hold a central place in leveraging nature's benefits, in terms of action plans as well as project delivery. Some participants mentioned working "closely", "very extensively", "on a day-to-day basis", "very often" with other Council services and partner organisations – some also show the breadth of entities they collaborate with: "community groups and volunteers and lots of specialist organisations and research bodies", "we collaborate a lot with residents and users", "pretty much every department", "comprehensive consultation lists", etc. One participant summarised the situation: "I don't think we do anything independent of anybody". Types of collaboration range from consultation and engagement to support and joint delivery. Participants mentioned collaborative work from strategy and planning – "a lot of planning, future developments, working with them on greenspace and nature" , "policy development or strategy"– to project implementation, for instance "activities relating to the actual environment and conservational biodiversity". Two participants mentioned hurdles to collaborative work: when discussing policy and strategy consultations, one of them talked about "capacity issues", which were perceived to cause "some things [to possibly] slip through". The other one felt that collaborations around SuDS were hindered because legislation was not clear enough regarding responsibilities around the maintenance of assets.

Despite these difficulties, it seems from the interviews that there has been a dynamic towards increased collaboration. In particular, the Edinburgh Adapts Partnership and the Edinburgh Biodiversity Partnership were cited as useful governance structures to ensure the integration of nature's contributions aspects across all relevant organisations in the City. Organisations involved in a Partnership come together in a steering group, where they work jointly on the development of action plans, their delivery and the monitoring of their progress. Participants perceived steering groups as critical structures enabling knowledge sharing and support among members – one participant said they "provide[d] support and facilitation" – as well as providing a formal structure where ownership and responsibilities for the different projects was made clear. One participant also stressed the importance of Partnerships in connecting individual actions to "join all [of nature's] benefits together". The participant felt this was the next stage for the Partnership with which they are involved with, as a "[step] upwards". Participants also mentioned the recent creation of structures such as the Green Infrastructure Working Group and the Climate Commission as spaces where nature's benefits are expected to be promoted. One participant reflected that there was "an increasing ethos in the city to work together as organisations or agencies, collectively".

5.4.2.4 Integration into high-level Council priorities

Ultimately, embedding nature's contributions into high-level priorities was stressed by many as a crucial long-term goal in ensuring they lead to "big outcomes" for health, well-being, adaptation to climate change and the economy. One participant described such an integration as "urban nature being the primary driver" of designing the urban landscape and stressed that nature's benefits would not be able to lead to significant societal outcomes unless they were considered at the strategic level.

There was a consensus among participants that integration into high-level priorities has yet to be achieved. Some participants mentioned that developing the urban natural environment is traditionally perceived as "not important, just nice to do" or as "one of the 20 things that you need to tick off". The traditional consideration of urban nature is seen as holding back the integration process: in this context, efforts in evidencing nature's value, raising awareness, and increasing collaboration, as described in the previous sections, are seen as means through which this hurdle could be lifted. As a result, some participants perceived progress in ES valuation methods, and especially standardisation, as instrumental in ultimately embedding the natural environment into high-level council priorities. However, it seems like two types of perceptions were actually entangled in the participants discourse: one that considered it important to improve current policies and processes using ES values and methods, and another one calling for a renewal of urban design principles based on ES considerations.

5.4.3 Perceptions of the ecosystem services concept

This aspect could not be discussed with one of the participants because of an emergency on their side. It was also impossible to reschedule. The following findings therefore refer to the contribution of four participants. For instance, it is with this sample in mind that expressions such as "all participants" are used.

5.4.3.1 Different definitions of ES

All participants but one had explicitly come into contact with the ES concept and felt able to provide a definition. All these participants have become familiar with it by working with colleagues and partners who were using the ES terminology – those people "who work in this area", "biodiversity and natural heritage colleagues", "definitely through research [. . .] It was mainly when Edinburgh University were running the OPERA programme". The definitions they provided varied from general to more specific.

Two participants defined ES as gifts from nature – "what nature gives us", "the benefits nature gives to society", "how nature provides services for free" – while the third talked of "what nature, all those greenspaces deliver in terms of outcomes or advantages". All participants stressed their understanding of ES as the breadth of benefits provided by nature: one participant mentioned "economic, social and health benefits", while another spoke of "the whole raft of things which I know [greenspaces] do deliver" and a third talked of a range of interests from "cultural ecosystem services" to "physical ecosystem services benefits from water". Participants also highlighted that ES are about linking nature to people and society, with expressions such as "to us", "to people", "to society", and elaborating on how ES "relates [biodiversity] back to how it supports everyone's life and wellbeing" and reflecting that "what it will come down to, is quality of living".

More specific perspectives on ES exist alongside this general definition of them being the breadth of nature's multiple (free) benefits to people and society. One participant viewed ES as benefits which cannot be replaced, or the replacement of which would incur large economic costs, citing pollination as an example. Another participant viewed ES as nature's benefits making a difference to people's quality of life, citing the following reasoning for identifying them: "if you remove those services, does that affect the quality of living in the city".

When defining ES, participants came to reflect about how the concept was "useful" or "valuable" to them. These reflections were further explored with a question about their experience using it and showed its importance in demonstrating nature's value. These aspects are presented in the next section.

5.4.3.2 ES as a way to demonstrate nature's values

Participants who were aware of ES perceived them not only as a concept, but also as a framework for measuring nature's benefits. In this context, the main role of ES consists in capturing the value(s) of nature, with participants mentioning spatial and economic assessments as well as more general "modelling work". One participant described valuation as "putting numbers around what we what we instinctively know", summing up the general perception of ES as a light shed on existing knowledge rather than fundamentally new information.

For two participants, capturing nature's value was especially useful for awareness-raising purposes. They qualified ES valuation as "helpful" and "valuable" in demonstrating to non-experts the relevance of nature to their own lives and well-being, even if they may not use the ES terminology when discussing it. One participant mentioned that nature's direct benefits to people, through "cultural services", was the focus of the earlier modelling work in which they were involved, while they perceived that regulating services were addressed by more recent efforts.

For the third respondent, valuing nature went beyond awareness-raising: this participant put an emphasis on operational matters and the role of ES in orienting decisions. In addition to “bringing them into the light”, the participant stressed the importance of understanding the relative importance of ES and the way they vary depending on possible actions. The participant also stressed the importance of ES valuation to advocate for resources for nature management.

5.4.3.3 The ES terminology, from expert to operational language

The experience with ES of participants who are familiar with them, revolves around collaboration with colleagues and partners. While participants report an “operational use” of the term with “biodiversity and natural heritage colleagues” or “our parks division”, it is the link with research which is especially highlighted. One participant mentioned ES were first part of the scientific language found in literature and research, and have since begun to move to operational language – “becoming increasingly the norm”. Other participants talked of the role of projects with the University of Edinburgh in mainstreaming the concept: one participant recalled a research programme which introduced them to ES and involved them in early modelling exercises; while another mentioned, as part of the action plan they are coordinating, current work led by the University on natural capital standards.

Contacts with academia have therefore introduced the ES concept and framework into the Council, in which they have started being used across departments and integrated into cross-cutting action plans. However, participants highlight that ES have not yet reached general language, with one participant noting that they were "still within the profession or within academia". Another participant, whose role involves awareness-raising within the Council and across partner organisations, said they were "definitely using the idea" with colleagues who do not have a scientific background, but were "using simpler language that's less of a barrier" with "the underpinning ideas [being] the same". The first participant shared their expectation that the continued efforts in explaining and using the concept would lead to its becoming "quite common" for the general public "in 10 years or so".

5.4.3.4 ES in the future: better integration into planning

All participants spontaneously talked about their expectations or wishes regarding the future place of ES within the Council. This includes the participant who was not familiar with ES before the interview.

ES were perceived as especially relevant for policies relative to planning in general and housing development in particular. Participants stressed that conditions on ES should be embedded "at an early stage" in planning applications for new infrastructure, which would require developers to measure ES losses and gains. One participant compared this expected progress to current requirements regarding biodiversity analyses and measures, predicting that "ecosystem services will be the next iteration of that". This participant described this scheme as part of "an ecosystem services monitoring process" they expect would be in place "within the next few years". In the same line, another participant mentioned a current project at the University of Edinburgh developing a natural capital standard for buildings.

More generally, supporting the integration of ES into Council policies appeared as one of the main roles of academia as perceived by participants. They mentioned a need for direction and guidance from experts, either through advances in valuation assessments, the development of robust tools or the development of ecosystem-services-related standards.

5.5 Discussing the integration of the ES concept in the City of Edinburgh

5.5.1 Lack of explicit integration

While a few occurrences of the term "ecosystem services" could be found in the reviewed documentation, the ES concept is not considered explicitly. As such, "ecosystem services" is yet another expression to describe nature's contributions to people, alongside words such as benefits or values. This lack of integration of the ES concept in strategies relative to the environment, greenspace, biodiversity or general planning has been observed in numerous instances, including in the cities of Berlin (Kabisch 2015, Hansen et al. 2015), Seattle (Hansen et al. 2015), various cities in Ontario (Lam & Conway 2018) and the Swedish county of Scania (Nordin et al. 2017). A study conducted in European and US cities found the most explicit references to ES in documents from Stockholm and New York, both in countries that started ES discourses early (Hansen et al. 2015). In Edinburgh, the ES concept is still currently seen as belonging to the expert and academic sphere: key informants refer to ES in the context of research projects or ongoing efforts to include valuation outcomes into specific parts of decision-making.

Interviews with key informants highlighted current efforts to include nature in climate change strategies and general spatial planning, including open spaces, housing and active travel. However, these efforts are sometimes conducted without explicit references to the ES concept, using instead language seen as non-expert. As noted in Lam & Conway (2018), not explicitly using the concept may constitute a missed opportunity to shape a common understanding of benefits provided by urban nature. By highlighting the cross-cutting quality of nature-related issues and facilitating a common terminology around nature's role, the ES concept has been shown to foster a better sense of synergies for greenspace creation and maintenance (Rall et al. 2015, Beery et al. 2016). It has also been suggested that the anthropocentric framing of the concept can be effective at generating political support for "greening" or environmental protection strategies (Schröter et al. 2014, Rall et al. 2015).

5.5.2 The contributions of nature to societal outcomes

Although the ES concept is not explicitly integrated into decision-making, the underpinning ideas were represented in the documents and in the informants' discourses: all documents contain at least one implicit mention of the concept; similarly, all informants acknowledged the role of nature and could give examples. This contrast between implicit and explicit integration has commonly been observed in Western European and US cities (Nordin et al. 2017, Hansen et al. 2015, Rall et al. 2015). It was also evidenced at the national level in Scotland, where there are good levels of conceptual integration but persistent difficulties in explicitly including ES knowledge into policy (Claret et al. 2018).

5.5.2.1 Framing of the discourse around ES

Analysing the documents and interviews within the IPBES conceptual framework gave insight into how the discourse around ES was framed. Two main types of contributions were acknowledged: the role of nature in improving health and well-being, and its part in addressing threats posed by climate change and pollution.

The link to health and well-being is emphasised in both documents and interviews. This recognition of the importance of nature for health and well-being has commonly been observed in the literature and stems from the widespread and long-standing acknowledgment of the benefit of greenspaces for the urban population (Cortinovis & Geneletti 2018, Kabisch et al. 2015). It is therefore noteworthy that the strategic document pertaining to health only contained anecdotal implicit references to the ES concept. An interview with public health officers would potentially have enabled more insight to have been gained into this very limited integration of nature into the document – however, as noted by Nordin et al. (2017) who found a similar result, it probably indicates a lack of understanding of the potential for nature to support public health efforts. Nevertheless, the publication of a Green Health Strategy by NHS Lothian in June 2019, following the establishment of a green health advisory board for Edinburgh and the Lothians, may lead to increased awareness of the benefits of nature by public health officers (Edinburgh & Lothians Health Foundation 2019).

The role of nature in climate change adaptation is more present in the discourse of interview participants than in the documents. The overall awareness of the contribution of nature to climate change adaptation is consistent with the increase in policy focus on climate change pressures, as noticed by Kabisch (2015) in Berlin and Frantzeskaki & Tilie (2014) in Rotterdam. In Edinburgh, the rise of public demand for better consideration of climate change aspects, leading to the declaration of climate emergency by both the City and the Scottish Government in 2019, may have played a role in the rise of awareness from the time the documents were released (2013 to 2018) to 2020 when the interviews were conducted. Whilst it seldom occurs in current strategies, the use of the “nature-based solution” terminology by those interviewees working in the biodiversity and climate sectors, also suggests an increased awareness of the techniques involved in addressing climate change. The language of interviewees around nature-based solutions, such as green roofs, SuDS or using the term “green infrastructure”, is reminiscent of the recognition in the documents of the role of the built environment in co-delivering ES. The links with the built environment are also likely to stem from traditional urban design and land use planning strategies, with provisions for built as well as (semi-)natural spaces (Lam & Conway 2018).

5.5.2.2 A contrasted perception of the individual services provided by urban nature

Non-material ES dominated references to individual services in the documents, which is a common result in the literature (Cortinovis & Geneletti 2018, Lam & Conway 2018, Nordin et al. 2017, Hansen et al. 2015, Wilkinson et al. 2013). As shown in diachronic analyses of planning documents, this predominance can be explained by the long-standing inclusion of the cultural meanings of parks and other greenspaces in urban design and planning strategies, especially regarding recreation (Wilkinson et al. 2013, Hansen et al. 2015). This is consistent with the mention of non-material services in a way or another by all interviewed Council staff, including the participant who was not aware of the ES concept. The interviewees often related non-material services to improved mental health, with one participant noting that the acknowledgement of the importance of nature for health was likely to gain momentum following the Covid-19 pandemic.

Along with non-material services, habitat provision was one of the most mentioned contribution in the documents – again a common result in the literature (Kabisch 2015, Lam & Conway 2018, Nordin et al. 2017, Hansen et al. 2015). Some have explained this predominance in a similar way to non-material services, arguing that habitat for species is a theme long discussed in nature conservation and which has permeated city strategies for some time (Nordin et al. 2017, Hansen et al. 2015). Others have linked the widespread recognition of habitats to the use of the related term of biodiversity as policy slogan that needs to be acknowledged, even though it may not be implemented in practice (Kabisch 2015, Piwowarczyk et al. 2013). The first explanation is more likely in the case of Edinburgh. Nature conservation and protection of wildlife has indeed been a practice there for many years – the City hosts Local Conservation Sites and Local Nature Reserves to which long-term projects are linked and which are protected by the Local Development Plan, which shows that habitat provision has indeed been mainstreamed into planning strategies. The awareness of the importance of wildlife may also be influenced by the presence of areas protected at national level under requirements set at various scales: examples include Ramsar sites (international), Special Protection Areas (European) or sites of special scientific interest (national). Furthermore, one interviewee explained that the biodiversity terminology had progressively infused the general language over the last 20 years, to the point where it is now a common term used by the Council and its stakeholders.

In contrast, the frequent mention of food growing in documents and by key informants is not a feature that has been widely reported in the literature. Only one study, conducted in Rotterdam, has discussed the attention to food growing, linked to the booming urban agriculture and gardening initiative in the city (Frantzeskaki & Tilie 2014). The situation seems different in Edinburgh, where food growing is an established practice which has been regulated since the late 19th century (Allotments (Scotland) Act 1892) and is currently managed through a specific piece of strategy (The Allotment strategy, see Table 5.1) as required by the Community Empowerment (Scotland) Act 2015. More generally, because This Act covers all local authorities in Scotland, other Scottish cities are likely to exhibit a similar pattern of mention of the food growing service.

The representation of regulating services in the documents and in the interviews offers an interesting insight into the role of high-level policy instruments in the consideration of ES at city-level. Overall, regulating services are less frequently mentioned than non-material services – a result observed in previous literature and likely attributable to a lower awareness of these services among practitioners (Kabisch 2015, Nordin et al. 2017). However, among the regulating services represented across the documents, flood protection / mitigation is mentioned at a frequency similar or higher than most non-material services, while services such as air purification or cooling are the object of a few references only. Where such a contrast has been identified in previous literature (Nordin et al. 2017), the authors noted that the services mentioned more frequently and elaborately were those related to areas covered by national legislation or policy, a factor that may also be relevant in the case of Edinburgh. Indeed, the provision of a flood prevention and mitigation service by urban ecosystems is embedded in Scottish regulation under the Water Environment and Water Services (Scotland) Act 2003 requiring the implementation of SuDS, and reinforced in the Flood Risk Management (Scotland) Act (2009) whereas the other regulating services are not directly covered by national policy or legislation. Interestingly, this difference across individual ES and sectors in national legislation has itself been shown to reflect differences in integration at the European level (Claret et al. 2018), suggesting that the integration of the ES concept in EU cities may be at least partly influenced by EU-level frameworks.

The analysis presented in the previous paragraphs points to the concurrent influence of two factors in the integration of individual ES into urban decision-making: traditional consideration in city planning and specific requirements in national legislation. In particular, and although climate change policies have been in place for some time, carbon storage and temperature regulation are among the services which have not fully permeated decision-making. The current emphasis on nature-based solutions may however lead to a better integration of these ES in the future and could raise the profile of poorly-represented air purification and noise attenuation.

5.5.2.3 Understanding of multiple benefits

Both in documents and in the discourses of interviewees, there is a recognition that ES can be delivered simultaneously. Multiple benefits are the most evident among non-material services, which are in effect perceived as a "bundle" provided by (formal) greenspace and contributing to well-being. Although this perception matches the findings of many bundle studies analysing the provision of non-material ES (Saidi &

Spray 2018), it may not accurately reflect the situation in Edinburgh. The bundle assessment conducted in Chapter 3, which shows that the "umbrella" services of contribution to physical activity and contribution to mental health are not consistently associated together, suggests that the non-material services identified in this Chapter – and contained in these two "umbrellas" – may not be either. Indeed, Chapter 3 suggests that the association between non-material services and formal greenspaces, which is one of the factors seemingly holding the non-material "bundle" together in the documents and the interviews, overlooks the fact that some non-material services can be provided by natural spaces which are not part of formal greenspaces: a typical example would be the passive enjoyment of street vegetation during a commute. Furthermore, the perception of non-material services as a bundle is also an indication of the scale adopted at strategic-level, where greenspaces as a whole have various structural features and therefore can provide multiple services (recreation, socialising, experiencing nature), while a site-level focus could potentially show trade-offs among them.

Regulating services are also seen as multiple benefits in the documents and the interviews. As evidenced by the participants' discourse, these services are perceived as linked by their role in addressing climate change and pollution. The biophysical reality in Edinburgh, as represented by bundles identified at data zone scale (see Chapter 3), is more nuanced. Although no trade-offs have been identified among the selected regulating services, they are not a homogeneous group either. Two distinct bundles have been identified, depending on the importance of tree cover in providing the services. The understanding of multiple benefits linked to climate change and pollution is therefore not necessarily consistent with the actual delivery of these services. For regulating as well as non-material services, the representation of multiple benefits is mainly made in relation to how they address societal outcomes rather than how they are delivered.

5.5.3 ES-based tools but not ES-based strategies

The content analysis of the documents shows a limited integration of the ES concept in strategical priorities and action plans, a result expected from the low awareness of the ES concept across sectors. The ES concept is not used to frame strategical priorities and action plans, but it was possible to identify measures which did aim at protecting or enhancing ES. They were categorised into four main types: managing landscape features, building stakeholders' capacity, fostering collaboration, and producing and using scientific evidence.

The management of landscape features is the most common type of ES-related actions across the documents, although no explicit references to ES are made. In line with Cortinovis & Geneletti (2018)'s findings, actions under this type tend to be traditional regulatory and design-based measures. In particular, this group of actions is the only one which includes statutory measures, for instance by making the maintenance of the ES delivered by trees mandatory or by requiring the provision of places dedicated to food growing. More generally, the ES and natural elements addressed in statutory measures echoes the emphases found in the information base of the reviewed documents: the most mentioned ES, habitat provision and food production, are those for which protection and enhancement are the most subject to requirements. Similarly, natural features which were the most mentioned in reference to the delivery of ES – trees, parks and allotments (Figure 5.10) – are all elements for which statutory measures exist. This supports the assertion that the descriptive texts supporting policy provisions primarily use the ES concept to show the value of assets for which planning and maintenance are subject to requirements.

The demonstration of nature's value is central to the use of the ES concept in actions related to capacity-building, collaboration, and the production and use of knowledge. Of these types of efforts, only those pertaining to scientific knowledge are explicitly associated with ES. Indeed, explicit references to the concept in published strategies are only made in relation to their measurement or modelling. Similarly, the reported explicit use of ES by interviewed staff focused on quantification projects. ES assessments in general, and monetary valuations in particular, are perceived as useful tools to advocate for conservation or enhancement projects when competing for budget resources. They are also seen as a gateway to the integration of nature into strategical priorities across sectors. However, interviewed participants with the closest links to ES-related issues perceived that this progress was impeded by the lack of suitable measures for the values of greenspace, such as standardised indicators which could be integrated into early planning stages. Kaczorowska et al. (2016) reported a similar concern from urban planning stakeholders in Stockholm, who found it difficult to draw on available ES data and were calling for material "adapted" to decision-making. Perceived gaps in available and accessible data in Edinburgh echo the emphasis for a stronger and more extensive evidence base at the Scottish national level (Claret et al. 2018), suggesting that challenges in integrating the ES concept in decision-making play across scales.

The focus on ES assessments suggests that ES are viewed less as a concept supporting the framing of strategies and more as a tool that supplements existing planning and policy instruments, without necessarily changing them (Hansen et al. 2015). Interviewed staff in Edinburgh viewed ES values as useful information to support specific actions, such as the development of business cases or the establishment of standards for housing development. At the same time, ES assessments are perceived as crucial for integrating nature into high-level priorities, because they provide a measure of its value to humans and can therefore prove to be a strong communicative argument (Kabisch 2015). However, this integration is not viewed as relying on using the ES concept to frame strategies. Although the ES concept may not be the only way to ensure that nature's benefits are leveraged for societal outcomes at strategical level, various studies highlight that structuring priorities and strategies with the concept could promote an integrative approach across decision-making areas (Hansen et al. 2015, Rall et al. 2015, Beery et al. 2016, Matzdorf & Meyer 2014). In Edinburgh, the importance given to collaboration across different areas, coupled with a good understanding of ES and existing actions to assess them, would be a favourable terrain for promoting ES-based strategies. Nevertheless, the explicit use of the ES concept in awareness-raising efforts may be a pre-requisite to furthering integration (Kabisch 2015). Furthermore, more research would be needed to understand the influence of national policies in fostering such an approach.

5.6 Summary

This Chapter uses a multi-method approach to analyse the awareness and understanding of the ES concept, as well as its inclusion in policies and strategical actions, in the City of Edinburgh Council services. The analysis of strategical documents and interviews with key informants show that the ES concept is not explicitly integrated in strategical decision-making: although the ES terminology is used to refer to nature's benefits in some sectors, the ES concept does not frame strategical priorities and action plans. Nevertheless, the ES concept is well understood in the planning, greenspace, biodiversity and climate remits: the role of nature in improving health and well-being, and in addressing threats from climate change, is acknowledged in the documents and the interviewees' discourses. In contrast, sustainability and health documentation seldom mentions the contributions of nature to societal outcomes.

The understanding and inclusion of ES in Edinburgh mainly focus on habitat provision, flood protection, food growing, and non-material services (such as recreation or experiencing nature). In line with findings in other developed cities, traditions in urban planning and requirements from national legislation are driving the emphasis on these specific ES. The scope of ES falling into decision-making interests can be expected to widen following increasing interest in nature-based solutions, in response to the current climate and pandemic crises. The potential role of bundles in raising awareness on the full range of ES delivered in urban areas is discussed in the next Chapter.

Furthermore, the understanding of the ES concept in the Council extends to the recognition that ES can be delivered simultaneously. In the documents and the interviewees' discourses, non-material ES are mentioned together as benefits delivered by formal greenspaces, while regulating services are perceived as linked by their role in addressing climate change and pollution. However, this "bundling" of ES may not reflect the actual spatial patterns of delivery: the next Chapter discusses the potential contribution of a bundle approach to shifting perceptions about multiple benefits.

Although the ES concept is not used to frame strategical priorities and action plans, measures to protect and enhance ES are included in the documentation. Apart from regulatory and design-based measures to manage landscape features, they mainly pertain to the demonstration of nature's value, to efforts in fostering collaboration, and to the production of scientific knowledge. Interviews with key informants confirm the place of the ES concept as a framework upon which to base planning tools and standards, rather than a way to reframe strategies or decision-making processes, a situation which has been documented in other locations. Nevertheless, the stated will to strengthen the role of nature in strategies, a demand for more ES-based evidence, and existing collaboration spaces around ES-related issues, are all factors that could lead to a further integration of the ES concept in Edinburgh.

The next Chapter uses the analysis conducted here to suggest ways bundles could contribute to decision-making processes, and to discuss how these contributions would be influenced by the decision-making context around ES.

Chapter 6

Discussion

6.1 Introduction

This Chapter aims to answer the thesis' general research question: "How could knowledge derived from ES bundle assessments be effectively used in decision-making related to land-use planning and management?", i.e.: "What conceptual, strategic, and instrumental uses of ES bundle knowledge would ease trade-offs between its salience, credibility and legitimacy, depending on the current mainstreaming of the ES concept?".

It brings together the results of Chapter 3 and Chapter 5 to address the thesis' specific questions and to outline avenues for future research. It includes four main sections, introduced in the following paragraphs.

Section 6.2 provides the basis for answering the research questions raised in this thesis, by addressing the second aim of the study - identifying and analysing the ES interrelationships that can be evidenced from the implementation of the developed bundle approach. Findings from the identification of ES Bundles and Spatial Bundles in Edinburgh are interpreted using analyses conducted in Chapter 3 and comparisons with the existing literature. By generalising these findings beyond the specific case of Edinburgh, section 6.2 paves the way to understanding how bundles of ES could help decision-making related to land-use planning and management.

The contribution of bundle knowledge to decision-making partly depends on its attributes of salience, credibility and legitimacy (Chapter 1): one of the thesis' aims is therefore to identify salience, credibility and legitimacy criteria for bundle knowledge, based on lessons-learnt from the case study. Section 6.3 addresses this aim by suggesting and describing criteria for the three attributes, based on lessons-learnt from the development of the thesis' bundle approach (Chapter 2), its implementation and discussion (Chapter 3 and section 6.2), and on the integration of the ES concept in strategic decision-making (Chapter 5).

The contribution of ES knowledge to decision-making can be conceptual, strategic, and/or instrumental; these different types of uses are influenced by the attributes of knowledge mentioned above and by the decision-making context (Chapter 1). Considering these factors, section 6.5 suggests five contributions of bundle knowledge across the three different types of uses outlined above. The section addresses the thesis general question by directly answering the specific question of "What conceptual, strategic, and instrumental uses of ES bundle knowledge would ease trade-offs between its salience, credibility and legitimacy, depending on the current mainstreaming of the ES concept?". It draws from the interpretation of bundle results (section 6.2), the criteria of salience, credibility and legitimacy (section 6.4); and the integration of the ES concept in strategic decision-making (Chapter 5).

Section 6.5 closes this Chapter by providing recommendations for future research, to further understand how ES are consistently associated, as well as the role bundle approaches could play in land-use planning and management. It suggests avenues of further research to address the limitations identified in this study and to test the hypotheses raised within the Chapter.

6.2 Discussion of patterns revealed by ES Bundles and Spatial Bundles

This section discusses in turn the main findings from Chapter 3:

- Identification of two distinct bundles across regulating and non-material ES (section 6.2.1))
- Lack of a consistent association between the two non-material ES included in the study (section 6.2.2
- Identification of a gradient of ES provision mediated by the proportion of tree cover and sealed areas (section 6.2.3)
- The role of food growing in some areas (section 6.2.4)

Each subsection briefly restates the finding, interprets it in light of other analyses in Chapter 3 and existing literature, outlines limitations and suggests general hypotheses.

6.2.1 Identification of two distinct bundles across regulating and non-material ES

ES Bundles and Spatial Bundles identified in this study show that the services of air purification, noise attenuation, habitat provision, carbon storage, temperature regulation, run-off retention, and contribution to mental health, are mostly provided together across the city. This finding is consistent with previous results from bundle studies showing positive associations across regulating and non-material services (see section 1.2.4). However, one important result is the identification of two distinct bundles: consistent associations were found among air purification, noise attenuation, habitat provision and carbon storage; similarly, temperature regulation, contribution to mental health and run-off retention are consistently associated together across the data zones.

According to the driver analysis of spatial bundles and the qualitative interpretation of PCA axes, differences in relationship with tree cover explains the two distinct bundles identified across the ES mentioned above. ES which can be provided by a diversity of land cover beyond trees are grouped together in a so-called "multi-bundle" (temperature regulation, contribution to mental health and run-off retention); in contrast, services which depend mainly on tree cover are gathered in a "tree-bundle" (air purification, noise attenuation, habitat provision and carbon storage). Bennett et al. (2009) classify ES interactions depending on whether they are due to a common driver or direct interactions across services. Here, the hypothesis of a common driver, namely the dependence on tree cover, is far more likely and in line with current knowledge of the processes underpinning the provision of the ES included in the study. However, the identification of these two bundles must be interpreted with a note of caution, as they may significantly depend on the assumptions made when quantifying the individual services (see Appendix C for details on the limitations of ES quantification methods used in the thesis). In this thesis, potentially relevant spatio-temporal factors, such as seasonal differences in vegetation cover, were not included; furthermore, the impact of man-made pressures such as air pollution, noise or building density were simplified. This thesis therefore offers what could be called a "first-order" analysis of bundles, which should be refined with the advances in ES quantification.

The identification of two distinct bundles can be compared with results from the PCA analysis conducted by Marsboom et al. (2018) for the city of Turnhout (Belgium). Even though the authors did not look for ES Bundles, their PCA plots suggest that biomass carbon, air quality regulation, and wood production are consistently associated together (fig. 3 in the article); an observation to which the "tree-bundle" of this thesis could be compared. Apart from this result, the differences in consistent associations found in Chapter 3 have not been previously described in the literature reviewed in Saidi & Spray (2018), namely the work of Baro et al. (2017) and Derkzen et al.

(2015): while no comparison is possible with Derkzen et al. (2015)'s study, as it focused on Spatial Bundles and did not identify ES Bundles, the two-bundle result differs from Baro et al. (2017)'s findings. In Baro et al. (2017)'s study of ES patterns in the Barcelona metropolitan region, all regulating and non-material ES included within the study were found to be consistently associated (air purification, climate regulation, erosion control, and outdoor recreation). This difference between their results and this Chapter's could be attributed to the difference in nature and extent of the study area: Baro et al. (2017) investigated ES patterns along an urban-rural gradient which includes the municipality of Barcelona, several adjacent middle-size cities and lower density towns, while this thesis focused on one city. The difference in detected consistent associations supports the findings of Marsboom et al. (2018) that a change in spatial extent which include parts of a different landscape – here the metropolitan region around a large city – leads to a reconfiguration of the detected bundles.

6.2.2 Lack of a consistent association between the two non-material ES included in the study

The PCA analysis shows that contribution to physical activity and contribution to mental health are not consistently associated with one another. This result can be explained by the reliance of these services on different types of land uses. The contribution of the city's public greenspace to physical activity depended on the proportion of the data zone area that was either at 5 min or 10 min walk to a public greenspace: as a result, the value of this ES depended on greenspace located inside and outside the data zone, and was not influenced by natural cover outside the boundaries of such spaces. In contrast, the contribution to mental health depended on the proportion of vegetation and water cover within a data zone, whether part of a public greenspace or not, and was not influenced by land use elsewhere.

The key assumption was that the contribution to mental health mainly relied on a passive experience of local natural areas, while formal greenspace was required for a contribution to physical activity. However, the pathways to improving physical and mental health are complex and this assumption may not hold true in all contexts. The scarcity of knowledge on these pathways also hinders the robustness of the quantification methodologies (see Appendix C for details on the limitations), which call for a cautious interpretation of the lack of consistent associations between contribution to physical activity and contribution to mental health identified in this Chapter. This lack of consistent association further supports the body of bundle literature suggesting that non-material services do not always occur together (Riechers et al. 2017, Ament et al. 2017). It contrasts however with the biophysical studies at other scales which show interlinkages among non-material services.

6.2.3 Identification of a gradient of ES provision mediated by the proportion of tree cover and sealed areas

The results of the clustering analysis, reported in Chapter 3, show five distinct levels of combined provision of air purification, carbon storage, noise attenuation, habitat provision, temperature regulation, run-off retention, and contribution to mental health. This common direction of variation is nuanced by a difference in gradient pattern between the ES belonging to the "tree-bundle" and those belonging to the "multi-bundle": the tree-bundle had a sharper decrease than the multi-bundle across the higher levels of provision, while the reverse happened across the lowest levels of provision. Furthermore, the spatial representation of the clustering analysis lead to three main findings. First, the groups of data zones with the highest levels of provision corresponded to areas with extensive tree cover, more specifically large wooded parks, and golf courses. In contrast, the lowest level was mostly found in the urban core, from the city centre to Leith. A third result lies in the identification of two distinct levels of provision across what can be defined as "residential" data zones, with those featuring small parks seemingly providing significantly higher levels of ES than those having limited greenspace (see section 3.6.6.2 for a description of these findings, including maps and graphs).

The common direction of variation identified by the clustering analysis was expected from the PCA findings, which showed an overall synergy among values of air purification, carbon storage, noise attenuation, habitat provision, temperature regulation, run-off retention, and contribution to mental health. Similarly, the differences in pattern between the tree-bundle and the multi-bundle across the five distinct levels of provision confirms the differences in associations revealed by the PCA analysis. As evidenced by regression analyses, the gradient of ES provision can be explained by the differences in tree cover and sealed areas across the city. The fact that an increase in "natural" ground cover leads to an increase in ES provision is an obvious result; as such, the significance of Spatial Bundles results lies elsewhere. First, they show a reliance on large areas of woodland for the provision of high levels of ES, therefore highlighting – or indeed confirming – the importance of large wooded greenspace for well-being, adaptation to climate change and pollution mitigation. Spatial Bundles also seem to evidence the role of small local greenspace in significantly improving ES provision in more constrained, residential areas. The value of Spatial Bundle results therefore lies in them bringing evidence from an ES perspective of the multi-faceted role played by nature in the city. As mentioned in section 6.2.1, the identification of these bundles must be interpreted with caution due to the assumptions made when quantifying the individual services.

A similar gradient delineation was identified in Baro et al. (2017)'s study of the metropolitan region of Barcelona, as four of the five clusters identified by the authors corresponded to an increasing level of ES provision: "urban core", "suburban nodes", "peri-urban green", and "forestland". Although the scale is different (municipalities vs data zones) and the sets of ES not identical, the analysis done in Chapter 3 corroborates the pattern highlighted by the authors: two high provision profiles are associated with large areas of woodland, and two low provision profiles are associated with the highest degrees of urbanisation. However, the influence of small greenspace, suggested in this Chapter by the identification of the "residential area – small greenspace" bundle, does not appear in Baro et al. (2017)'s study. The difference in scale of assessment may explain this discrepancy: because the authors investigated ES patterns across the region's urban-rural gradient, they were interested in variations across municipalities rather than neighbourhoods. As a result, their analysis does not reflect small scale differences in land cover within urban areas.

The five-level Spatial Bundles detected in this study only partially match the results obtained by Derkzen et al. (2015) in Rotterdam. Similar extremes can be observed in both cases, with an "urban core" grouping of neighbourhoods where ES provision is the lowest and a "major city parks" grouping where ES provision is the highest. Furthermore, in both studies a majority of neighbourhoods have a moderate level of ES provision. However, Derkzen et al. (2015)'s analysis does not identify significant dissimilarities among the "major city parks" neighbourhoods, while this study distinguishes between "urban forest" and "Parkland & golf courses". In addition, no significant differences were identified in Rotterdam among the neighbourhoods with a moderate provision of ES, while two bundles were delineated in this thesis ("residential areas" and "residential areas with greenspace"). There are three possible explanations for these differences in patterns across the gradient of ES provision. First, the higher spatial resolution of the analysis in this thesis ($4.7km^{-2}$) than in Rotterdam (81 neighbourhoods in a $326km^2$ area, meaning a resolution of $0.25km^{-2}$) could suggest that the variations reflected by the additional Edinburgh bundles cannot actually be detected at the scale at which the Rotterdam study was conducted. This explanation supports the suggestion made by Raudsepp-Hearne & Peterson

(2016) that scale influences the identification of bundles. Second, a difference in clustering method may have contributed to the identification of a higher number of levels of ES provision in Edinburgh than in Rotterdam. This explanation is supported by the results of section 3.6.5, where some of the tested methods led to the identification of three distinct levels instead of five. Third, this difference in patterns may reflect an actual difference in urban form between the two cities. The distribution of tree and sealed cover may vary between them, leading to distinctive ES variations and the identification of a more detailed gradient in Edinburgh. The potential impact of differences in urban form is supported by two elements. First, the presence of large water surfaces in Rotterdam led to a water-specific bundle which was not identified in Edinburgh, which shows that a difference in urban structure had an effect on bundle configuration. In addition, the "urban core" bundle in Rotterdam is spread out across the city while it is concentrated in the centre in Edinburgh, further suggesting a difference in urban form across the two cities.

6.2.4 The role of food growing in some areas

The clustering analysis shows that food growing is occurring at three different scales in Edinburgh, from small allotments (bundle "Small allotment") to larger community or professional growing (bundle "Food & Woodland") to extensive areas dedicated to agricultural activities (bundle "Agriculture"). The data zones corresponding to Allotment and Food & Woodland bundles also exhibited a relatively high provision of the other ES.

The impact of food growing in the delineation of bundles might be seen as surprising in an urban area. Here, the identification of food-specific bundles was due to the high variation of values across the city. This explanation is supported by the fact that food-specific bundles were not identified when high variations were suppressed before clustering. As detailed in section 3.6.6, the inclusion of these bundles was ultimately a subjective decision driven by the importance food growing holds in Edinburgh. The similarity in profiles between, on the one hand, the “Allotment” and “residential with small greenspace” bundles, and on the other hand, the “Food & Woodland” and “Parkland & golf courses” bundles, may be explained by the provision of food growing spaces alongside or within other greenspace at two different scales. However, the interpretation of the different profiles of food-specific clusters is limited by the high uncertainty surrounding the valuation of the food growing service. In the absence of better data, land use covers of allotments and agricultural land were used as proxy, which may have prevented the identification of potential additional patterns linked to other factors such as productivity.

In the literature, food-specific bundles are commonly identified in studies where agriculture is a salient feature (e.g. Raudsepp-Hearne et al. (2010)). In particular, Baro et al. (2017)’s study of the Barcelona metropolitan region found a bundle dominated by crop production among a pattern of more “urbanised” ES profiles. However, the food growing service has not been included in previous city-scale bundle assessments (Derkzen et al. 2015, Riechers et al. 2017), likely due to a lower importance of urban agriculture in the studied areas.

6.3 Generalisation to other urban settings

6.3.1 ES Bundles

The identification of a tree-bundle and a multi-bundle across a city’s neighbourhoods can be expected in most urban areas because of the biophysical processes underpinning the provision of the regulating ES in these bundles. Two elements can be expected to vary across cities: first, the strength of associations within the bundles are likely to be influenced by factors such as ambient temperature, the configuration of the road network, or the levels of air and noise pollution generated by road traffic. That is because these factors would have an impact on some ES (e.g. air purification) but not others (e.g. carbon storage). Second, the belonging of non-material ES to either one of the two bundles is likely to be influenced by the cultural aspects around greenspaces as well as their level of access and quality. Indeed, the differences in association patterns identified in the literature for non-material ES, and the uncertainties linked to the associations found in this thesis, suggest that the interlinkages among them may be specific to biophysical, planning, management and cultural contexts.

6.3.2 Spatial Bundles

The identification of groups of neighbourhoods sharing similar profiles of ES, characterised by an increasing level of provision depending mostly on the proportion of tree cover, can be expected to hold true in most cities. However, the number of distinct levels of ES provision and their spatial location is likely to depend on the distribution of natural cover (in general) and tree cover (in particular). The specific results obtained in Edinburgh regarding the number of gradients and how ES vary across them can be expected to be found in cities sharing a similar structure and historical zoning, i.e. featuring a heavily built-up core area, medium-density residential neighbourhoods, some large parks, and contained within a green belt. However, a similar ES bundle gradient will likely not be found in cities with different urban forms and histories than Edinburgh. Two examples of such cities can be drawn. First, the New Towns developed in post-war UK, which followed a different urban pattern than established settlements, resulting in a different configuration of urban centres, industrial estates, residential areas and greenspaces (Deltoro Soto et al. 2018) Second, sprawling cities in North America and Europe, which lack the urban-rural boundary provided by greenbelts in the UK (TCPA 2014) and may include urban morphologies leading to different ES patterns than the ones identified in Edinburgh.

The identification of food-specific bundles can be expected in other cities where urban agriculture is a common practice, for instance in some UK cities. However, the identification of three scales of food growing may be specific to Edinburgh, where parts of the Green Belt are located within the city boundaries and lead to the existence of medium to large scale agricultural activities.

6.4 Ensuring the salience, credibility, and legitimacy of bundle results

The potential use of bundle results – conceptually, strategically, or instrumentally – is partly influenced by the extent to which these results are salient, credible, and legitimate (Chapter 1). This section draws from findings reported in Chapters 3 and 5 to identify and describe the following key aspects:

- Salience:
  - Capture of all trade-offs and synergies at a meaningful scale
  - Identification of drivers for the evidenced trade-offs and synergies
  - Conveying of information in the right format
- Credibility:
  - Systematic consideration of potential bundle solutions
  - Quantitative analysis of drivers
  - Consideration of uncertainties
- Legitimacy:
  - Participatory approach to the assessment
  - Recognition of different stakeholders' needs

Although these aspects are addressed in separate subsections, I recognise that they are in fact interrelated (see Chapter 1): throughout the section, I have tried and mentioned how the different aspects may influence one another. I have also tried and highlighted how the influence of the above aspects may differ depending on the type of use for bundle results (conceptual, strategic, instrumental).

The scope of this section is limited to characteristics specific to bundles, although relevant issues overlap with ES assessments in general. Furthermore, the aspects described in this section focus on spatial studies, as opposed to other types of bundle approaches listed in Chapter 1 (Table 1.2).

6.4.1 Salience

The salience of bundle results refers to their relevance to the needs of decision-makers regarding instrumental decisions, conceptual discussions or strategic positions (see Chapter 5, section 1.2.2 for an introduction of these terms). Drawing from the implementation of a bundle approach described in Chapter 3, and on the current decision-making context regarding the integration of the ES concept (Chapter 5), ensuring the salience of bundle results means:

- Ensuring they capture all trade-offs and synergies at a meaningful scale, which involves:
  - Selecting ES based on both scientific consideration and decision-makers priorities; and
  - Choosing a scale of assessment consistent with the level of decision-making targeted.
- Identifying drivers for the evidenced trade-offs and synergies; and
- Ensuring they convey information in a format accessible to decision-makers.

The following subsections detail each of the three points above.

6.4.1.1 Capturing all trade-offs and synergies at a meaningful scale

The main purpose of identifying bundles is to detect consistent ES associations across a landscape. In order to get a full understanding of the trade-offs and synergies at play, it is crucial that all ES of importance to the area, whether this importance is perceived or not by stakeholders, are included in the assessment. The practice of selecting ES through a participatory process, which is common in applied ES assessments, is even more crucial for bundle studies. If ES within the priorities of decision-makers are not included in a bundle study, even though they may be less important than other ES regarding their contribution to societal outcomes, there is a risk of missing an opportunity of showing how multiple benefits can be achieved or trade-offs mitigated. As an illustration, carbon-related aspects currently have a high profile in Edinburgh City Council, as indicated for instance by the publication of a road map for carbon neutrality (Williamson et al. 2019), and the recent valuation of the City's trees in storing and sequestrating carbon (Doick et al. 2017). These initiatives make for a context in which carbon-related ES should be included in a bundle study, even though the contribution of urban nature to the mitigation of greenhouse gases emissions is likely to be small (section 3.3.3.3). The strategy in the thesis was to include the ES for which evidence of a significant contribution was the strongest: this ES, carbon storage, relates to the prevention of carbon emissions, for which there is a stronger evidence of contribution than mitigation.

In the bundle literature, the main driver for the selection of ES is indeed the "importance for the region" or the "expected demand", but rarely have spatial assessments sought inputs from stakeholders or implemented a full participatory approach to identify relevant services (see Baylan & Karadeniz (2018) for a notable exception). In this thesis, the input of the Manager of the City's Parks & Greenspace service was crucial in the selection of ES, especially when it came to carbon-related aspects (see above and in section 3.3.3). By sharing with him my initial understanding of nature's contributions in the city, I initiated a dialogue around what his service has been able to evidence in the past, and what the priorities of the Council and local residents were. This discussion played an important role in my decision to include a carbon-related ES in the assessment. However, it is worth noting that an extended participatory approach to the selection of ES, for instance including other Council services, Council partners (e.g. NHS Lothian, Scottish Wildlife Trust) and local community groups (e.g. Friends of Parks), may have led to a different set of ES. The study of the integration of the ES concept in Edinburgh suggests pathways towards such an extended participatory approach. On the one hand, the lack of explicit integration of ES at the strategic level, as well as a perception of nature's contributions focused on recreation, habitat, food growing, and flood protection, means that pedagogy and awareness-raising would be required as part of the participatory process. On the other hand, there are strong indications of effective collaborative processes, such as Partnerships and regular joint work with user groups, which could facilitate the implementation of a participatory approach.

While a concerted selection of ES would reduce the risk of missing synergies or trade-offs relevant to the study area, the scale at which these ES are valued and bundled may influence the nature of the detected ES associations (see section 6.2 for discussions on scale). The influence of scale was not studied in-depth in the thesis, not least because datasets with tens of thousands of spatial units would involve a prohibitively high memory consumption with the bundle approach developed here, which is based on the computation of distance matrices (Chapter 2). Although it is not possible here to ascertain the extent to which bundles would be reconfigured by a change of scale, a possible reconfiguration makes it even more important for a bundle study to enquire about the scale at which synergies and trade-offs are to be considered by decision-makers.

In Edinburgh for instance, the context around ES makes two scales relevant. On the one hand, an ES mapping exercise is currently being conducted at high resolution in the context of the Ecological Coherence Plan (The City of Edinburgh Council 2019): the relevance of a bundle assessment conducted at that scale would reside in its grounding in these efforts, and could provide additional information on opportunities to act on synergies or avoid trade-offs locally. On the other hand, the need for more ES-based evidence at strategic level, in order to address the stated ambition to work with nature to achieve societal goals (see Chapter 5), makes the data-zone scale a relevant one through which to identify ES synergies and trade-offs. At that scale, it is easier to get them "at a glance" or to identify areas of priorities (see section 6.5). Interactions with the Greenspace service, and with senior staff in other remits, were invaluable in understanding which scales were relevant. In particular, seeking feedback from the Greenspace service built confidence in choosing the data zone scale, as interest was shown even if the service was not used to working from this perspective.

There is an apparent tension between two aspects of salience: on the one hand, the implementation of a participatory approach to the selection of ES (and scale), would allow bundle results to address decision-makers' priorities more closely. Legitimacy and credibility would also be positively impacted. On the other hand, the timelines involved with such an approach may not fit those associated with the development of overarching strategies or policies. Navigating this 'speed-quality' trade-off would require a joint design of the research, that would be based on the communication of deadlines and on iterative exchanges involving, for instance, the presentation of early and mid-term results (Sarkki et al. 2014, 2015). As an example, in this study, the collaborative approach to building the list of studied ES also optimised time, in addition to building trust and legitimacy: instead of conducting a time-consuming literature review to identify ES, I performed a rapid review to build a robust scientific foundation: communicating the results of this review enabled a discussion with the Council that led to a complementary targeted review, leading to a final list of relevant ES. More generally, the iterative approach implemented in this study, i.e. seeking regular feedback and inputs as knowledge was produced (see Table 1.4), has proven valuable as a method to ease trade-offs across the project (see also sections 6.4.1.2 and 6.4.2.1).

6.4.1.2 Identifying drivers for the evidenced trade-offs and synergies

Identifying drivers for bundle results means understanding why some ES are consistently associated together and / or why some spatial units have a similar ES profile. Driver identification brings salience to bundle results in two main ways. As highlighted by research such as Dade et al. (2019) or Spake et al. (2017), driver identification is crucial if synergies are to be promoted and / or trade-offs avoided.

In this study for instance, the level of combined ES provision in bundles is driven by tree cover and sealed cover, which are characteristics which could be levers of action in planning. The identification of drivers could also contribute to the salience of bundle results because it would allow the statistical confirmation, or not, of some factors. For instance, the importance of trees in delivering urban ES has been recognised, both in the literature on individual services (see references for the methodologies developed in section 3.4) and in city-level strategies (e.g. the Edinburgh Trees & Woodland strategy). The analysis conducted in this thesis statistically confirms the importance of trees as a driver for the provision of multiple benefits, but also highlights the role of other types of land cover in delivering a full range of benefits.

Beyond a simple identification of drivers, the ability to understand changes in bundles, e.g. in levels of combined ES provision, under different scenarios, would enhance the salience of bundle results if bundle findings are used instrumentally. For instance, such a driver identification strategy could involve testing different types of urban forms for land in (re-)development [1]. Nevertheless, trade-offs could arise between the need to build scenarios which are complex enough to credibly reflect reality, and the need for these models to provide clear and simple outcomes. Furthermore, the inclusion of different perspectives in the development of bundle-related scenarios, as has been done in previous ES assessments (e.g. Mckenzie et al. (2014)), would participate in the salience of the results, in addition to enhancing their legitimacy. However, because instrumental uses of scenarios are likely to be tied to specific timelines, challenges in ensuring the timely production of scenario outcomes and including a diversity of perspectives can be expected. As mentioned in the previous section, addressing this challenge would require a close relationship between the research and policy teams. For instance, in the context of this thesis, regular interactions with the Greenspace service allowed me to become familiar with the emerging Ecological Coherence Plan for the City: if a bundle approach were to be embedded into such a plan, these interactions would have identified a framework with timelines around which to adapt.

6.4.1.3 Conveying information in the right format

The identification of bundles allow multiple ES to be considered simultaneously, but they come with the risk of an increased cognitive burden in interpreting ES information (Wright et al. 2017). As a result, a simple and uncluttered presentation of bundle results is crucial for their salience. In this study, as in many other spatial bundle assessments, results were presented using a PCA plot and a map accompanied with ES profiles. Depending on decision-makers' level of familiarity with statistical analyses, such results may have to be presented in a different way; for instance, a diagrammatic representation of information embedded in a PCA plot may be helpful (Figure 6.1). This type of representation was presented to the Manager of the Greenspace service

[1]Such a strategy is being implemented for the cooling service in the NatCap project *Golf and Natural Capital, Twin Cities, MN, USA* (https://naturalcapitalproject.stanford.edu/projects/golf-and-natural-capital-twin-cities-mn-usa)

to confirm their clarity.

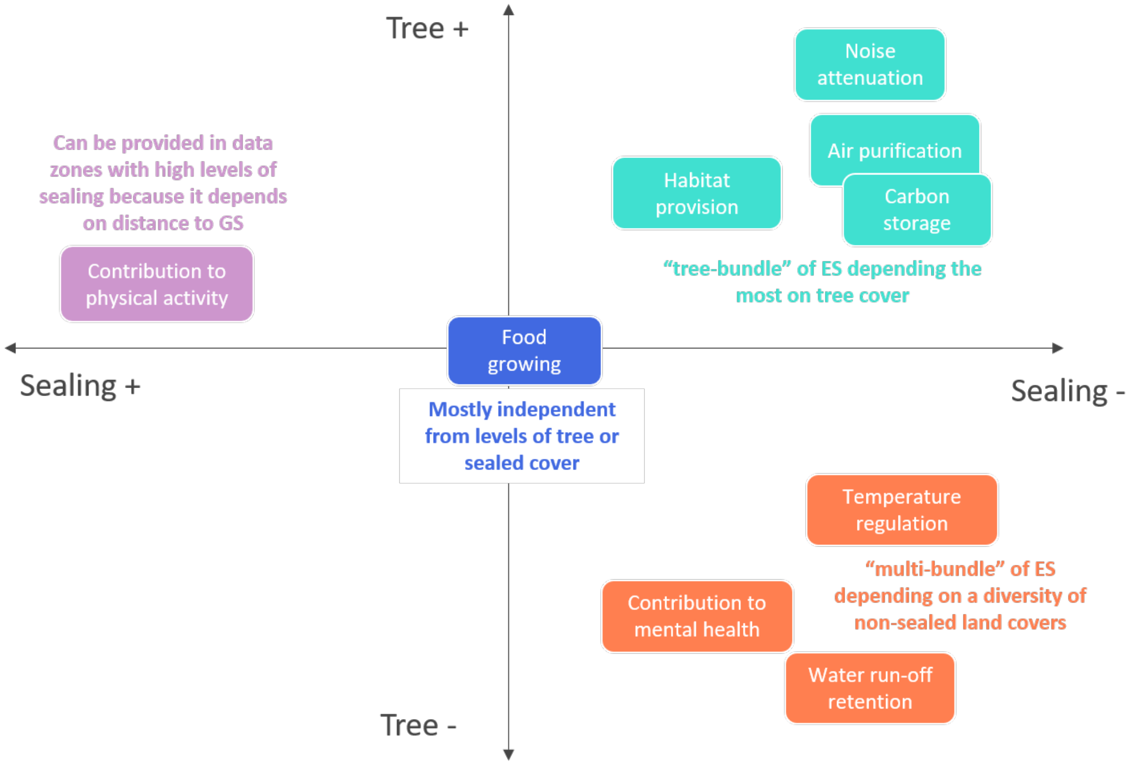

Figure 6.1: Example of a representation of ES Bundles in a simplified PCA plot

Similarly, detailed ES profiles showing the distribution of ES values around the median are important for estimating uncertainties (see Appendix D.4), but may distract from the main message for a non-expert audience (see section 6.4.2.3). In Edinburgh, the Greenspace service has extensive experience with ES data, which would allow conveying complex information; however, in a context where ES assessments are seen as crucial in demonstrating nature's value (Chapter 5), a simplified synthesis of bundle results would be necessary.

The way bundle findings are communicated has an impact on how they are likely to be used. For instance, simple messages derived from bundle results can be helpful for awareness-raising in early stages of the decision-making cycle; they could also be used strategically by decision-makers to support existing views (Sarkki et al. 2014). This would be the case in the short-term in Edinburgh, as suggested by interactions with senior staff across different remits (Chapter 5). Communication of complexity can be relevant at various stages of the decision-making cycle: early on, it could be valuable in conveying the inherent complexity of ES associations (Young et al. 2014); in later stages, it could also be helpful in order to directly support decisions – for instance using detailed maps for different scenarios.

Conveying information in the right format also participates in the legitimacy of a bundle approach, by acknowledging that different stakeholders have different needs. In this thesis, regular interactions with the Greenspace service, and semi-structured interviews with senior staff in various remits, were valuable in outlining relevant format to communicate bundle results. Understanding the current mainstreaming of nature in the different sectors, as well as governance structure of the different remits, is necessary to enhance the salience of bundle knowledge on this aspect.

6.4.2 Credibility

The credibility of bundle results refers to their reliability and trustworthiness (see Chapter 1, section 1.2.2). Drawing from lessons learnt from the development of this study's bundle approach (Chapter 2) and from the analyses conducted in Chapter 3, three key features of credible bundle results can be identified:

- Systematic consideration of potential bundle solutions;
- Quantitative analysis of drivers; and
- Consideration of uncertainties.

The following subsections detail each of the three points above.

6.4.2.1 Systematic consideration of potential bundle solutions

If we place ourselves in the common case of identifying bundles from spatial assessments using biophysical indicators, then bundling involves analysing a multivariate dataset with variables *measured in different units*. In order to enable comparison and grouping, these variables must be standardised; additionally, a transformation step may be helpful in discovering consistent associations (Chapter 2).

The bundle assessment reported in Chapter 3 shows that a robust approach to the choice of standardisation and transformation methods is crucial to achieving credible bundle results. First, standardisation can have an impact on the types and number of bundles identified, which highlights the relevance of testing different standardisation methods. Methods under consideration should also be meaningful for the distribution of ES values: for instance, in urban areas where ES distributions are highly skewed, standardisation based on the mean would not reflect original values accurately. In the bundle literature, the rationale for choosing a specific standardisation method is often not justified – particularly not in relation to the distribution of the original dataset. There is therefore a possibility that some relevant spatial patterns have been missed, thereby impacting the salience of bundle knowledge in addition to its credibility.

When it comes to transforming the dataset in this thesis, it was initially thought that (i) consistent associations may be more apparent and robust on transformed datasets, and (ii) magnifying the differences in the bulk of skewed data may help in detecting associations. However, while transforming the dataset did lead to potential bundle solutions, these solutions showed less detailed patterns than the ones obtained without transformation: by reducing the differences in higher values, transforming the dataset prevented the discrimination between two types of synergetic hotspots. Therefore, testing different transformation methods, including a "no transformation" option, was invaluable in identifying meaningful patterns in the thesis.

More generally, the systematic consideration of different possible bundle solutions in Chapter 3 has highlighted the unintended bias that can come from choosing a specific combination of preparation steps without considering a range of options. For instance, some solutions mainly grouped data zones based on the area they dedicate to food growing, a result due to the considerably high spatial variation of the food growing service compared to the other ES. These solutions were missing important patterns hinted in the tb-PCA plot, which also indicated that food should play a minimal role in shaping the bundles.

This example, as well as the points above regarding standardisation and transformation, show that a systematic consideration of many solutions may be necessary to ensure the credibility, but also the relevance of bundle results to decision-making. More broadly, a systematic consideration also participates in building legitimacy, as it brings transparency to the bundle determination process and reduces the risk of unintended bias when choosing the "best" bundle solution. Nevertheless, a systematic generation and consideration of multiple solutions is a complex and lengthy process – although it is likely to enhance the credibility and legitimacy of bundle assessment, careful attention would have to be paid to the decision-making timelines in order to ensure the salience of associated bundle results. In this regard, iterative interactions across stakeholders would be crucial in easing the trade-off between salience on the one hand, and credibility on the other (Rosenthal et al. 2014, Sarkki et al. 2015).

6.4.2.2 Quantitative analysis of drivers

As introduced in Chapter 1, a quantitative identification of drivers based on a list of putative relationships between ES associations and factors linked to land cover or socio-economic characteristics, is necessary to ensure the reliability of bundle interpretation (Spake et al. 2017). One of the limitations to the identification of drivers is the element of circularity mentioned in Chapter 1, where the variables tested as drivers have also been used to derive ES values (Spake et al. 2017). It is the case in this study, as the simplest regression models with the highest accuracy were obtained using land cover characteristics, even though a wider range of variables were tested (results not shown). These models provide information beyond the simple fact that bundles depend on tree and sealed cover: they allow determination of *how* bundle attribution may shift depending on these characteristics. Because not all urban ES depend on tree or sealed cover in the same way, the nature of the relationship between the latter and bundles were not trivial, which makes the regression analysis valuable despite the circularity effect.

Nevertheless, it is important for the credibility of bundle results that the identification of drivers allow predictors to be uncovered from variables which were not used to derive the individual ES values. In this study, the predictive power of variables linked to socio-economic deprivation and housing types were tested, which resulted in poor results (results not shown). More investigation would be necessary to identify underlying drivers of tree and sealed cover. For instance, a time-series analysis of bundle patterns, as conducted by Renard et al. (2015) in Quebec, would allow to gain insight into the historic evolution of urban land cover and provide more information as to which socio-economic or institutional factors would be relevant.

A quantitative driver analysis could provide decision-makers with levers on which to act to obtain "desirable" bundles: such an analysis would therefore be especially important for the credibility of an approach seeking instrumental uses of bundle results. For instance, interactions with senior staff in Edinburgh highlighted a need for quantitative evidence of multiple benefits and how to achieve them. Furthermore, a quantitative analysis of drivers would also influence conceptual and strategic uses positively, since activities such as awareness-raising or advocacy would benefit from the credibility brought by the analysis. The identification of quantitative drivers is also the opportunity to enhance the legitimacy of a bundle assessment, by ensuring decision-makers and other stakeholders are included in the identification of potential factors and levers of action. Even though a participatory approach to the scoping of putative drivers would increase the chances of including relevant levers of action, thereby also increasing the salience of the assessment, a tension between speed and quality of the assessment could arise. As mentioned in previous sections, close relationships and joint design of the research across the research and policy spheres would help in managing this tension.

6.4.2.3 Consideration of uncertainties

Uncertainty in ES assessments is diverse and complex, and its consideration in ES research is still emerging (Hamel & Bryant 2017, Lautenbach et al. 2019). Uncertainties in bundle assessments can be characterised according to their nature, source and level – a typology suggested by Walker et al. (2003*a*) and used by Hamel & Bryant (2017) in their opinion on ES uncertainty assessments. The nature of uncertainty in bundle studies is both ontological and epistemological. Ontological because bundle results are affected by the inherent variability of natural processes (e.g. PM_{10} absorption in tree leaves), human behaviours (e.g. in accessing greenspace) and societal dynamics (Walker et al. 2003*a*, Schulp et al. 2014). Epistemological because bundles are ultimately a simplified representation of human-nature interrelationships, which are subject to complex feedbacks and unpredictable behaviours (Ainscough et al. 2018). As noted by Walker et al. (2003*b*), it may be difficult to identify precisely what is reducible through investigations and research, and what is irreducible because it is an inherent property of coupled natural and social phenomena.

The technical sources of uncertainties in spatial ES assessments mainly relate to indicator definition, GIS data, and mapping methodology (Schulp et al. 2014, Kangas et al. 2018). Limitations of clustering, ordination, and regression analyses are additional technical sources of uncertainty specific to bundle studies. Furthermore, bundle studies (and indeed all ES assessments) are subject to uncertainties from "unknowns unknowns", which go beyond technical aspects – as models have limited capacity to predict system behaviour that has not previously appeared, and may be entirely blind to aspects of the total system (Ainscough et al. 2018). When it comes to level of uncertainty, bundle studies attempt to limit uncertainties linked to "unknowns unknowns", by offering an integrated ES assessment of a specific system.

Salient bundle approaches, as defined in section 6.4.1, should be scoped and designed with the consideration of multiple perspectives, which further contributes to limiting blind spots prevalent in "standard" ES assessments. However, as suggested by Funtowicz & Ravetz (1993) and Ainscough et al. (2018), efforts in addressing non-technical sources of uncertainties often result in a higher level of technical uncertainty. This trade-off between credibility and legitimacy is indeed magnified in bundle studies, as bundle identification accumulates the uncertainties which propagate from spatial data and processes through to individual ES values.

The diverse nature, multiple sources and high level of bundle uncertainty call for the inclusion of uncertainty assessments in bundle studies. Because it would be clear to stakeholders associated with a bundle study that significant uncertainties exists, failing to assess them may undermine the use of results in any of the three ways considered in the thesis (conceptual, strategic, instrumental,) (Hamel & Bryant 2017). Decision-making processes routinely involve risk assessments of different strategies, so that instrumental uses of bundle results would be expected to include similar analyses. Even when bundle results are not intended to directly shape a decision, an uncertainty assessment is crucial for stakeholders to understand which claims are the most robust, therefore contributing to awareness-raising and strategic uses (Pappenberger & Beven 2006). Nevertheless, not all bundle studies may require the same level of attention given to uncertainty: exploratory studies, or those aiming to raise awareness, may not require an extensive uncertainty assessment and / or a high level of accuracy; however, those aiming for a direct use in decision-making would need to demonstrate their robustness more confidently. The fact that processes already exist for uncertainty assessments, and that these assessments can be tailored to the specific decision-making context, means that the consideration of uncertainties in bundle studies would not jeopardise the production of timely outputs – in other words, the trade-off between salience and the consideration of uncertainties would not be severe. More attention should be paid to the trade-off with legitimacy, as described in the previous paragraph: uncertainties assessments should be carefully planned in order for different perspectives to be included, while ensuring technical uncertainties are manageable in decision-making timeframes.

Based on best practices in decision-making support, guidance suggested by Hamel & Bryant (2017), and lessons-learnt from this Chapter, one can outline possible elements to ensure the credibility of bundle results regarding uncertainty:

- Focusing on sources of uncertainty which can be expected to have the strongest effect on bundle results. For instance, it could mean focusing on ES exhibiting the largest spatial variation, or on those for which data sources are the least reliable. This focus would involve propagating uncertainty for a selected number of services.

- Preferring simple quantitative treatment of many uncertainties to a complex one dealing with one specific source. For instance, a simple quantitative propagation using standard error measurements or value bounds, as exemplified in Chapter 3 for some ES, could provide the basis for assessing uncertainties of the subsequent bundle identification. Bounding ES values could be done by considering multiple sources; in particular, stakeholder participation could be invaluable in providing information on extreme values or factors absent from the original data sources.

- Running sensitivity analyses based on bounded values of individual ES. Sensitivity analyses are a common practice in decision-making support practice. For bundle results, they could rely on previous uncertainty assessments of the individual ES under consideration – these assessments would focus on a selection of ES and would prefer simple quantitative methods (see previous points).

- Communicating uncertainties without impeding the communication of results. Bundle analyses already yield information-dense outcomes, including PCA plots, maps and graphs (see sections 3.5 3.6), making the addition of another layer of information challenging for the clarity of the resulting product. In that regard, bundle studies can draw from approaches in geospatial science such as two-dimensional legends, where one axis would code the bundle assignation and the other the extent to which it is deviates from the bundle "centre".

6.4.3 Legitimacy

Legitimacy refers to the inclusion of diverse values enabled by an unbiased and fair process of knowledge production. In the previous sections, I highlighted the value of deliberative and participatory approaches to a salient and credible identification and analysis of bundles, including the selection and valuation of ES, and the identification and analysis of potential drivers (van Oudenhoven et al. 2018, Lopes & Videira 2017, Kenter 2016). Beyond an active engagement of stakeholders, acknowledging their importance in the knowledge production process is also important - it would rely on a transparent bundle determination process, and consideration of different stakeholders' needs and expertise when conveying findings and assessing uncertainties.

In this thesis, regular communication with the Manager of the Greenspace services, Mr Jamieson, built trust and confidence around methodological choices and produced knowledge. Sharing results throughout the study also enabled to develop communication formats that enabled meaningful discussions. The relationship I built with Mr Jamieson meant that I was comfortable enough to ask him for contacts of senior staff across services, in order for me to assess the integration of the ES concept in the Council (see section 4.4.2). His knowledge of the different strategies and action plans across remits was also invaluable in bringing confidence to my analysis of the decision-making context around nature in Edinburgh (section 5.2). The interactions I had with Mr Jamieson and his colleagues nourished my reflections around the identification of uses for bundle knowledge; in the later stages of the study, Mr Jamieson's inputs on a preliminary list of these uses also played a role in developing and describing them (section 6.5).

The scope of this study is limited to identifying uses for bundle knowledge, by understanding how this knowledge can be salient, credible and legitimate – it did not however include a real-life testing of these uses. The legitimacy of such a project would need to rely on a fuller participatory approach than the one conducted in this thesis (see section 6.4.1).

6.5 Proposed uses of bundle results

Bundle assessments provide knowledge on the associations among multiple ES (section 1.2.4). For instance, in this thesis, two different groups were identified across regulating and non-material services; additionally, a gradient of ES provision mediated by the proportion of tree cover and sealed areas was identified (section 6.2). The salience, credibility and legitimacy of this knowledge, and of the processes for producing it, plays a major role in whether and how the evidence would be used (section 1.2.2 and 6.4). Another influencing factor is the current integration of the ES concept in decision-making, as an indication of the mainstreaming of ES. For instance, this thesis shows no explicit integration of the ES concept in Edinburgh - as in most cities - even though there is some understanding of the underpinning ideas, a stated need for more ES-based evidence, and a will to strengthen the role of nature in city strategies (Chapter 5). Because bundle knowledge can be considered policy-relevant based on the literature, but it is not currently policy-demanded (section 1.2.5), this context is likely to play an important role in the types of uses that can be effectively achieved.

Based on the discussion of bundle results and their attributes (section 6.4), and the decision-making context analysis of Chapter 5, this section identifies conceptual, strategic and instrumental uses which are relevant to the current ES integration in urban decision-making, and which limit the trade-offs between salience, credibility and legitimacy:

- Raising awareness about multiple benefits from nature (conceptual use)
- Shifting perceptions of multiple benefits (conceptual use)
- Advocating for the protection of, and better access to, the natural environment in woodlands, large parks, and golf courses (strategic use)
- Advocating for multifunctional residential gardens and local greenspaces (strategic use)
- Prioritising land-use planning and management actions (instrumental use)

These uses are described in the next subsections using the following structure: first, the problem addressed by the use is stated; then, the potential contribution of bundles is detailed; lastly, a comment on the influence of the decision-making context is provided, using the example of Edinburgh where possible.

These uses were presented to, and discussed with, the Manager of the Greenspace service. This process allowed to specify and amend a first draft of potential uses.

6.5.1 Raising awareness about multiple benefits from nature (conceptual use)

6.5.1.1 What is the challenge?

The range of ES relevant to urban areas is wider than the limited set of ES dominating the perception of nature's contributions in urban decision-making - namely recreation, habitat provision, flood protection, and to some extent food growing (see Chapter 5). Such a narrow focus may undermine the provision of, or fail to harness synergies with, other contributions of nature. This is even more an issue in the context of increasing pressures from climate change and the loss of biodiversity.

6.5.1.2 How could bundles help?

One of the elements hindering a wider integration of ES at strategic level is a limited understanding within decision-making sectors not directly associated with nature of the role of ES in achieving societal outcomes. Improving the consideration of nature throughout different remits in city government could therefore be initiated by raising awareness of the full range of ES, how they are associated with the "traditional" ones listed in 6.4.1.1, which ES are most associated together and as a result, how jointly achieving different outcomes could happen.

A bundle approach that is relevant and legitimate would first allow the identification of the full range of ES relevant to the socio-environmental goals of the city, by including, in a fair and unbiased way, the contributions of various stakeholders in city government and external organisations. In Edinburgh, these stakeholders could include senior staff in the different directorates, councillors, governmental agencies and user groups. Then, the identification of consistent associations would show how ES which are currently poorly explicitly addressed, such as cooling or carbon storage, relate to recreation, habitat provision or flood protection, thereby evidencing how co-benefits may be delivered, and where they are currently absent. It would also show how ES which contribute to different societal outcomes are consistently associated together (see also section 6.4.2), and would highlight to the related stakeholders opportunities for synergies. A visual, non-technical representation of the results would be especially important since the results would be primarily addressed to stakeholders with a limited knowledge of ES.

6.5.1.3 How would the decision-making context regarding ES integration influence this use?

Existing collaborative structures where awareness could be raised, as well as political recognition of the importance of greenspaces, would favour the use of bundle results to raise awareness about multiple benefits. For instance, in Edinburgh, the current decision-making context is likely to facilitate this use. Senior staff in nature-related remits are familiar with ES assessments and have expressed a need for more ES knowledge to demonstrate nature's value, which could be addressed by bundle results. Furthermore, the role of nature in preventing or mitigating the impacts of extreme climate events and public health issues is also increasingly acknowledged at a strategic level, as shown by the leadership of the city regarding biodiversity, the recent creation of a Green Health partnership, and the emergence of nature as a central element in place development. This acknowledgement could mean an improved receptivity of decision-makers to bundle knowledge and an increased likelihood of an actual rise in awareness.

6.5.2 Shifting perceptions of multiple benefits (conceptual use)

6.5.2.1 What is the challenge?

This thesis has identified two main potential misconceptions at a strategic level regarding how ES may be simultaneously provisioned:

- In documents and interviews, ES are bundled depending on whether they contribute to well-being or adaptation to climate change, which can lead to the misperception that they are provided distinctly, whereas some non-material services and regulation services are actually provided together at data zone scale.

- Regulating ES tend to be mentioned together even though they may not be biophysically bundled: for instance, air purification is frequently mentioned alongside flood protection in the documents, when they actually belong to different bundles at data zone scale.

These misconceptions may result in underestimating (point 1 above) or overestimating (point 2) the type and level of multiple benefits delivered by urban nature.

6.5.2.2 How could bundles help?

Bundles could provide evidence to shift perceptions about how ES are associated together, by providing a visual representation of ES consistent associations and elements of explanation about their drivers. As mentioned in the previous section, showing consistent associations between health-related and climate-related ES would highlight opportunities for synergies across sectors – it could also show at a higher level how two strategic aspects could be tackled simultaneously. The fact that some regulating ES are not consistently provided together would show that that different types of land forms are necessary across the city to maximise the contribution of nature to addressing climate change and pollution issues.

This use of bundle results would be most relevant for decision-making areas where the ES concept is already understood to some degree, for instance through knowledge of "ecosystem-based", "natural capital" or "nature-based solutions" approaches. Because bundle results would challenge current perceptions, a clear and transparent communication of its reliability and trustworthiness, especially regarding the management of uncertainties, would be needed. A robust and participatory identification and analysis of drivers would also be an important feature, as they would provide strong arguments for shifting people's perceptions.

6.5.2.3 How would the decision-making context regarding ES integration influence this use?

The elements raised in section 6.5.1.3, suggesting an enabling context in Edinburgh, also apply here. In addition, the fact that regulating ES are not necessarily bundled together would not be a strong challenge to perceptions: the importance of trees, which played a critical role in shaping the identification of regulating bundles in this thesis, is recognised in Edinburgh within decision-making areas related to nature, to which this use is addressed.

6.5.3 Advocating for the protection of, and better access to, the natural environment in woodlands, large parks, and golf courses (strategic use)

6.5.3.1 What is the challenge?

This study shows that the highest levels of combined provision of multiple ES occur in data zones with large wooded parks and golf courses (bundles "Urban Forest" and "Parkland & golf courses"); similar results were also obtained in other locations (section 6.2.3). The contribution of these spaces to the provision of ES across the city is therefore crucial. Furthermore, most ES deliver benefits at a local scale (section 3.3.4), which means that accessing large wooded greenspace likely plays an important role in these ES contributing to people's quality of life. However, reduced public funding and development pressures threaten the integrity of these spaces (Mell 2018). In addition, restricted or difficult access to some of these spaces, both real and perceived, hinders their contribution to people's quality of life (Wolch et al. 2014, Zhang et al. 2017).

6.5.3.2 How could bundles help?

Bundles provide quantitative evidence of the importance of large wooded parks and golf courses for delivering multiple benefits to people. By bringing such evidence from an ES perspective, and therefore adopting an anthropocentric framing to the protection and enhancement of large greenspaces, bundle assessments may be able to help generate political support. Their strength would reside in their visually showing the gradient of ES provision across the city, with maps and graphs such as the ones drawn up in section 3.6 . Bundle assessments could be used by biodiversity and greenspace officers to advocate for the protection of, and better access to, large greenspaces. A participatory approach to the selection and valuation of included ES, attention to the format of findings, and a brief explanation of the uncertainties, would be important success factors of this endeavour.

6.5.3.3 How would the decision-making context regarding ES integration influence this use?

Existing political commitments or interest towards ES-related topics, such as green infrastructure or nature-based solutions, would enhance the receptivity of decision-makers to advocacy based on bundle findings. For instance, the current climate-driven interest for nature-based solutions, as well as increasing public concern for biodiversity, could factor in this receptivity. Furthermore, the evidence provided by bundles could help to quantitatively confirm existing planning policies, such as the Large Greenspace Standard in Edinburgh, which requires all homes to be within 800m walking distance of an accessible large greenspace of at least 2 hectares. Lastly, the existence of effective collaboration spaces, to gather support beyond the greenspace and biodiversity remits, could help amplify bundle findings.

6.5.4 Advocating for multifunctional residential gardens and local greenspaces (strategic use)

6.5.4.1 What is the challenge?

Although large greenspaces exhibit the highest provision of ES, there is some evidence that tree cover and the presence of growing spaces makes a significant difference within residential areas (bundle “residential” vs bundle “residential – small greenspace”, see section 6.2.3). The presence of local greenspaces and domestic gardens, especially with some tree cover, is therefore likely to contribute to people’s quality of life by providing multiple ES. However, the value of such spaces may not be acknowledged or upheld; there is for instance a growing trend of paving over domestic gardens in the UK (Perry & Nawaz 2008).

6.5.4.2 How could bundles help?

Similar to the point made in the previous section, bundles would provide quantitative evidence, from an ES perspective, of the importance of small local greenspaces. Nevertheless, the influence of the land cover and configuration of these spaces, as well as the wider urban form to which they belong and the cultural context around them, is not sufficiently known (section 6.2.3). As a result, advocating for small local greenspaces would need to rely on a strong driver analysis, showing how differences in land use lead to differences in bundle distribution. The choice of scale would be especially important is such bundle assessments to ensure that the impact of small greenspace can be picked up in the analysis (section 6.2.3). In addition, and similar to the previous section, a participatory approach to the selection and valuation of included ES, attention to the format of findings, and a brief explanation of the uncertainties, would be important success factors for this use of bundles.

6.5.4.3 How would the decision-making context regarding ES integration influence this use?

As for advocacy for large greenspace (previous section), existing political commitments towards ES-related topics and existing collaboration spaces would favour the contribution of bundles. For instance, in Edinburgh, bundles could help to quantitatively confirm the relevance of the Small greenspace standard, which requires all homes to be within 400 metres walking distance of a 'good' quality, accessible greenspace of at least 500 sq.m.

6.5.5 Prioritising land-use planning and management actions (instrumental use)

6.5.5.1 What is the challenge?

Because most urban ES lead to local benefits, the gradient of ES provision evidenced by spatial bundles shows an uneven exposure of people to multiple benefits across the city. In parallel, research has shown that access to greenspaces, especially the larger and good-quality ones, is often enjoyed by the less disadvantaged in terms of income, education or ethnicity (Rigolon 2016, Wolch et al. 2014, Nesbitt et al. 2019). The uneven accessibility of urban greenspace has therefore been acknowledged as a socio-environmental issue in many parts of the world (Wolch et al. 2014), and in particular in the UK (Forest Research 2020). Further concerns have been arising from the intensification of these inequities by urban greening agendas and interventions (so-called "green gentrification"): there has been an uneven response to existing inequities in the provision of greenspace, and little capacity to ensure the provision of benefits and access for all residents (Anguelovski et al. 2019). In this context, understanding the impact of different planning or management options on the socio-spatial distribution of urban ES could be beneficial.

6.5.5.2 How could bundles help?

Bundles provide a simplified way to visualise the different levels of access to multiple benefits from greenspaces. Cross-analyses with socio-economic data, such as the Scottish Index of Multiple Deprivation (SIMD), could provide information on the link between socio-economic status and level of access to multiple ES. Such an analysis could help identify priority areas for intervention, for instance by highlighting data zones combining high deprivation with an assignation to a lower-provision bundle. The development of quantitative scenario analyses, testing the impact of different patterns of land use on the distribution of bundles, could also help prioritise planning and management actions.

6.5.5.3 How would the decision-making context regarding ES integration influence this use?

The decision-making context would play an important role in this direct application of bundle assessments into planning and management decisions. The recognition, by decision-makers, of multiple benefits from greenspace and how they are delivered, is likely to be a pre-requisite (see conceptual and strategic uses in sections 6.5.1 and 6.5.2). The ES concept may also have to be explicitly integrated into the city's strategies and policies before decision-makers become receptive to bundle results. Furthermore, as with any type of scientific knowledge, the timing of a bundle assessment would have to align with decision-makers' priorities.

6.6 Future research

6.6.1 Increasing the accuracy of urban ES models

The identification of consistent associations among ES is dependent in part on the accuracy of the spatial quantification methodologies for the individual ES included in the study. Future bundle assessments in urban areas should consider the following adjustments to the methodologies developed in this thesis:

- Composition of private gardens: since network of gardens play an important role in the provision of some ES, a more context-specific determination of garden composition would improve the assessment. An option would be to take a random sample of gardens across the city and determine their composition using remote sensing data. Mean values could then be derived and standard errors computed.
- Air purification: including in the assessment the influence of tree species and sizes, configuration of tree patches, and road traffic air pollution levels. However, more empirical research on the influence of these factors are needed for them to be robustly included. This is even more true for vegetation types other than trees.
- Noise attenuation: including in the assessment the influence of tree type and size, configuration and size of tree patches, density of tree planting, and noise pollution levels. More empirical research on the influence of these factors is however needed for them to be robustly included.
- Carbon storage: inclusion of the contribution of urban soil based on recent studies quantifying below-ground carbons sinks in urban greenspaces (eg. Lindén et al. (2020))
- Habitat provision: introducing more sensitivity into the scoring system by representing differences within habitat networks, e.g. between core habitats, moderate networks and high-dispersal networks.
- Temperature regulation: using the "Urban cooling" InVEST model, which calculates an index of heat mitigation based on shade, evapotranspiration, albedo, distance from cooling islands (e.g. parks), and building intensity. This model addresses some of the limitations of the methodology developed in the thesis, by

considering city-specific temperature and vegetation data, as well as the impact of the built environment.

- Run-off retention: inclusion of the contribution of SuDS features and the influence of topographic factors such as slope. A better assignation of soil type to the different vegetation covers may also have an impact on the value of the service, as would be better data on surface sealing.

- Food growing: going beyond land cover as a proxy for the service. More research would be needed on two fronts: first, to quantify the amount of food produced by urban agriculture (for instance using indicators linked to yields or to the amount of money saved by households); and second, to quantify the impacts of food growing activities on aspects related to health and well-being, such as physical activity or socialising.

- Contribution to physical activity: including in the assessment the influence of size, land cover configuration, quality, and exercise-related facilities in public greenspaces, as well as a better estimation of travel time and access to these spaces. More empirical research on the influence of these factors is however needed for them to be robustly included.

- Contribution to mental health: disaggregation of this "umbrella" ES into two or three ES describing different dimensions or determinants, for instance: socialising, active contact with nature, or passive experience of nature. A participatory selection of these ES would increase the salience of the bundle approach (see section 6.4.1). However, the links between these non-material ES on the one hand, and factors such as land cover and structure, greenspace quality and access on the other hand, are not well-known and likely to be context-dependent. Therefore, quantitative social research methods should be explored for the valuation of these ES; for instance, the use of large scale surveys should be explored for the valuation of these ES. Such methods would also be relevant for the assessment of the Contribution to physical activity and the non-material aspects linked to food growing mentioned above.

6.6.2 Evaluating uncertainties

As mentioned in section 6.3.1.2, the assessment and communication of uncertainties is of great importance to the credibility of bundle studies. In this thesis, ranges of uncertainties were estimated for each individual ES: future work could involve an assessment of how these uncertainties propagate to the identification of bundles. For instance, a sensitivity analysis could be conducted using the bounding values of the uncertainty ranges.

The influence of clustering methods on the stability of the bundles identified in this thesis could also be tested. For instance, using self-organising maps (Dittrich et al. 2017) or RGB maps based on PCA results (Marsboom et al. 2018) to identify Spatial Bundles could provide insights into how different algorithms influence the detection of ES associations.

6.6.3 Exploring ES associations across scales

Spatial resolution is likely to influence the ES associations detected by a bundle assessment, as indicated by the comparison of Chapter 3's results with existing studies (section 6.2). Another argument for the exploration of ES associations across different spatial resolutions is the varying scales of provision across the ES selected in the study (section 3.3.4 in Chapter 3), which could make it likely that associations at neighbourhood scale do not carry at high resolution, for instance for an assessment with 25m x 25m spatial units. As a result, future work could focus on analysing the differences among ES Bundles or Spatial Bundles identified at different resolutions. Such work may require adapting the clustering methods used in this thesis to allow an analysis on a very high number of spatial units.

6.6.4 Investigating ES associations in various urban contexts

The identification of a distinct "tree-bundle" and "multi-bundle" across urban ES, as well as the identification of Spatial Bundles characterised by an increasing level of ES provision, can be expected to hold true in most cities (sections 6.2.1 and 6.2.3). Nevertheless, the strength of associations across ES Bundles, as well as the number of distinct levels of ES provision and their spatial location, is likely to depend on urban morphology and cultural as well as institutional contexts.

As a result, further work aiming to develop a full picture of ES associations in urban areas could rely on multiple case studies to investigate the influence of different urban morphologies and cultural contexts. For instance, one could imagine two pairs of cities of similar size, climate, and cultural context, with:

- Pair 1 sharing a similar spatial structure as Edinburgh (radial with an urban core, residential areas, large parks and a green belt);
- Pair 2 sharing a similar spatial structure, but different from Edinburgh: for instance, pair 2 could be comprised of two New Towns from the same decade.

The influence of the cultural context could likewise be investigated by two pairs of case studies, with Pair 1 the same as above, and Pair 3 sharing a similar urban morphology with Pair 1, but located in different cultural and institutional contexts – for instance in Western or Northern Europe. The choice of case studies across the three suggested pairs could be informed by literature on urban gradients (McDonnell & Hahs 2008), in particular the application of the urban gradient concept to the study of urban ES (Tratalos et al. 2007, Grafius et al. 2018).

The differences in ES patterns identified in such pairs of case studies would allow the formulation of more specific hypotheses on the stability of bundles across different urban contexts. It could also help in identifying bundle drivers linked to urban form or cultural and institutional factors. The identification of such driver types could also be brought by the study of bundles across time in a specific location: for instance, identifying bundles at different points in the history of Edinburgh could allow to link changes in detected associations to changes in urban form and / or cultural and institutional elements.

6.7 Summary

This Chapter identifies potential uses for bundle approaches in land-use planning and management at city scale, based on the implementation of such an approach, and the study of ES integration in decision-making.

The Chapter started with a discussion of the four main findings that can be drawn from the bundle assessment conducted in the thesis. The identification of two distinct bundles across regulating and nonmaterial ES, the lack of a consistent association between the two non-material ES included in the study, the identification of a gradient of combined ES provision, and the role of food growing, form the basis on which potential uses for bundle approaches were then identified.

The outcomes of implementing a bundle approach in this thesis go beyond the results themselves. The assessment gave insights into how to ensure the salience, credibility, and legitimacy of bundle results - all attributes likely to influence the actual use of bundles in decision-making. A salient approach should capture all trade-offs and synergies at a meaningful scale, identify drivers for the evidenced trade-offs and synergies, and convey information in a format accessible to decision-makers. Credibility would rely on a systematic consideration of potential bundle solutions, a quantitative analysis of drivers, and an estimation of uncertainties. Based on salience and credibility aspects, a legitimate approach would ensure the participation of stakeholders in the assessment, a transparent bundle determination process, and a consideration of stakeholders' needs and expertise when conveying bundle findings and uncertainties.

Drawing from the discussion of bundle findings and attributes, as well as the extent to which the ES concept is integrated into decision-making, five potential uses for bundle results are described in this Chapter. Bundle results could help raise awareness about multiple benefits from nature and clear misconceptions about how these combined benefits are provided (conceptual uses). They could also assist in advocating for large and small greenspaces: on the one hand, the protection of, and better access to, the natural environment in woodlands, large parks, and golf courses; on the other hand, the creation and safeguarding of residential gardens and local greenspace (strategic uses). Lastly, bundle results could directly contribute to prioritising land-use planning and management actions (instrumental use).

Conclusion

This study seeks to understand how knowledge derived from ES bundle assessments can be effectively used in land-use planning and management. The thesis focuses on high-level decision-making at city scale, relying on a case study in the City of Edinburgh and adopting an interdisciplinary approach, complemented by an iterative collaboration with the City's Parks & Greenspace office, characterised by regular feedbacks and inputs.

First, bundles of ES are identified and analysed using geospatial and statistical analyses (addressing the first and second aim of the thesis), providing insights into the salience, credibility, and legitimacy of bundle results (third aim). Second, the decision-making context around ES is explored by studying the integration of the ES concept therein, using content analysis of policy documents and semi-structured interviews (fourth aim). These two pieces of research are then brought together to discuss how bundle assessments could be used conceptually, strategically, and instrumentally (fifth aim).

The identification of bundles of ES in urban areas has proven challenging compared to other landscapes researched in the literature, due to the heterogeneous and zero-inflated spatial distributions of urban ES (Chapter 2). The approach developed in this study therefore pays close attention to the choice of statistical methods to identify and analyse bundles, building on existing practices and the consideration of the dataset structure. This includes an emphasis on validation steps to ensure both the quality and interpretability of results.

The application of the bundle approach developed in Chapter 2 to the area of Edinburgh located within the by-pass, at data zone scale, leads to four main findings (Chapter 3, Chapter 6):

- Two distinct ES bundles are identified among the regulating and non-material ES included in the study: although all these ES are provided together across the city, consistent associations are found, on the one hand, among ES which depend mainly on tree cover ("tree-bundle": air purification, noise attenuation, habitat provision, and carbon storage) and on the other hand, among ES which can be provided by a diversity of land covers beyond trees ("multi-bundle": temperature regulation, contribution to mental health, and run-off retention). The identification of such distinct bundles has not been previously described; a fact which could be attributed to differences in the scale of the assessment compared to previous studies, both in terms of extent and resolution.

- No consistent association was found between the two non-material ES included in the study: contribution to physical activity and contribution to mental health. Although this finding challenges the results of biophysical studies in other landscapes, which tend to show strong synergies among non-material ES, it supports the body of bundle literature suggesting that they do not always occur together in cities.

- Five distinct levels of combined ES provision are identified across the city, mediated by the proportion of tree cover and sealed areas, and characterised by a difference in gradient pattern between the ES belonging to the “tree-bundle” and those belonging to the “multi-bundle”. The distribution of these spatial bundles highlights the importance of large areas of woodland for the provision of high levels of ES, and subsequently for well-being, adaptation to climate change and pollution mitigation. Spatial bundles also evidence the role of small local greenspace in significantly improving ES provision in more constrained, residential areas. Similar patterns of combined ES provision have been identified in the literature, but differences in the gradient structure points to the importance of urban morphology for both the spatial distribution, and the ES profile, of spatial bundles.

- Food growing is occurring at different scales, from small allotments to extensive areas dedicated to agricultural activities. The identification of these food-specific bundles reflects the importance of urban agriculture in Edinburgh, as they are usually identified in studies where agriculture is a defining feature of the landscape. This result also highlights the impact of a highly-dispersed variable on the identification of bundles.

These findings should be considered in the context of the often-high level of uncertainties involved in the quantification of the individual ES. As such, the results presented here can be viewed as a "first-order" analysis, to be refined along with advances in ES quantification.

These results, and the assessment process itself, shed a light on the salience, credibility and legitimacy criteria that would be needed for a bundle approach to effectively contribute to decision-making (Chapter 6):

- The salience of a bundle approach would rely on it capturing all trade-offs and synergies at a meaningful scale; identifying drivers for the evidenced trade-offs and synergies; and conveying information in a format accessible to decision-makers;

- The credibility of a bundle approach would lie in its systematic consideration of potential bundle solutions; quantitative analysis of drivers; and consideration of uncertainties; and

- The legitimacy of a bundle approach would rely on a transparent bundle determination process, and consideration of different stakeholders' needs and expertise when assessing uncertainties and conveying findings.

Trade-offs among these attributes mainly stem from the difficulty of producing salient knowledge in timeframes that enable processes for credibility and legitimacy. These trade-offs are likely to be less intense for conceptual uses, for which salience of bundle knowledge is not linked to the direct use of bundle results into decisions. Furthermore, tensions between salience on the one hand, and credibility and legitimacy on the other hand, can be eased by joint design and production of research, including an iterative approach seeking regular feedback and inputs.

The thesis recognises that the extent to which bundle knowledge can be salient, credible and legitimate, including the extent to which the trade-offs among these attributes can be eased, also depend on the decision-making context around ES. By analysing the integration of the ES concept in strategic documents and in the perceptions of senior Council staff, Chapter 5 provides insights into how bundles could be used, and which factors could impede or favour these uses. The analysis, conducted according to the multi-method approach developed in Chapter 4, shows that:

- In Edinburgh, as is the case in most cities, the ES concept does not frame strategical priorities and action plans, although the ES terminology is used to refer to nature's benefits in some sectors. The role of nature in improving health and well-being, and in addressing threats from climate change, is acknowledged in the planning, greenspace, biodiversity and climate remits in Edinburgh - but is seldom mentioned in the health and sustainability areas.
- The inclusion of ES in Edinburgh mainly focuses on habitat provision, flood protection, food growing, and non-material services. In line with findings in other developed cities, traditions in urban planning and requirements from national legislation is driving the emphasis on these specific ES.
- There is a recognition that ES can be delivered simultaneously: non-material ES are mentioned together as benefits delivered by formal greenspaces, while regulating services are perceived as linked by their role in addressing climate change and pollution. This analysis of the perception of multiple benefits

conducted in Edinburgh has not been part of previous assessments of ES concept integration.

- Apart from regulatory and design-based measures to manage landscape features, measures to protect and enhance ES mainly pertain to the demonstration of nature's value, efforts in fostering collaboration, and the production of scientific knowledge. In Edinburgh, the ES concept is more seen as a framework on which to develop planning tools rather than a way to reframe strategies, which a common feature shared with other cities.

- A stated will to strengthen the role of nature in strategies, a demand for more ES-based evidence, and existing collaboration spaces around ES-related issues, are all factors that could lead to a further integration of the ES concept.

The main limitation of this investigation relates to issues with participant sampling. Due to restrictions imposed as a result of the Covid-19 pandemic, interviews could not be conducted with senior staff in some of the relevant sectors, especially health. A fuller coverage may have identified additional elements influencing a potential contribution of bundle results.

The results and reflections summarised above, considered in relation to one another, provide insight into ways bundle results could be used conceptually, strategically, and instrumentally (Chapter 6):

- Raising awareness of the full range of ES delivered across a city, by showing how lesser-known ES are associated with the traditional ones, as well as the different types of associations - a visual, non-technical representation of the results would be especially important for this conceptual use. It would also be facilitated by an existing collaborative environment and a political recognition of the importance of greenspaces.

- Shifting perceptions about how ES are associated together, as the policy discourse around simultaneous delivery of ES may not fully match the biophysical bundling of their provision. Because bundle results would challenge current perceptions, a clear and transparent communication of its reliability and trustworthiness, especially regarding the management of uncertainties, would be especially needed for this conceptual use. Furthermore, this use would be most relevant for decision-making areas where the ES concept is already understood to some degree.

- Supporting the protection of, and better access to, urban forests and large parkland, in a context where funding and socio-economic issues increasingly undermine their capacity to contribute to people's quality of life. By providing quantitative evidence of their importance for societal outcomes, bundle assessments may help generate political support, using visual representations of the gradient of combined ES provision across the city. A participatory approach to the selection and valuation of included ES, attention to the format of findings, and a brief explanation of the uncertainties, would be important success factors of this strategical use.

- Advocating for multifunctional residential gardens and local greenspaces, in a context where the value of such spaces may not be acknowledged or upheld, by providing quantitative evidence that tree cover and the presence of growing spaces makes a significant difference within residential areas. This strategical use would need to rely on a better knowledge base than currently available, regarding the influence of the land configuration of these spaces and their surrounding environment.

- Prioritising areas for intervention, in a context where the uneven accessibility to nature's benefits has been acknowledged as a socio-environmental issue in many urban areas across the globe. Bundle-based assessments could for instance highlight spatial units combining a high deprivation level and an assignation to a lower-provision bundle, and directly influence planning decisions. This instrumental use would especially depend on the level of awareness of decision-makers to the multiple benefits from greenspace and how they are delivered, and on the timing of a bundle assessment.

The findings of this thesis, as listed above, contribute to increasing the knowledge base on ES associations and on the integration of the ES concept in city-level decision-making. On the methodological side, it introduces the systematic consideration of different clustering solutions for the identification of spatial bundles, and provides general guidance for assessing bundles at a city scale. It also suggests a methodology for an extended assessment of the integration of the ES concept, based on the IPBES conceptual framework and including an analysis of the representation of multiple benefits. Findings from the thesis provide an improved understanding of ES associations and patterns in cities, including quantitative and visual evidence of multiple benefits. Due to the high uncertainties linked to the valuation methods developed in this study, the bundle analysis presented here can be seen as a scoping assessment, which should provide nonetheless a strong basis for further work. Furthermore, the analysis of the integration of the ES concept in Edinburgh confirms the trends shown in other cities in the developed world, in addition to providing new information on the perceptions of the simultaneous provision of ES. Last but not least, this thesis constitutes yet another step towards an improved consideration of ES in decision-making. The discussion regarding salience, credibility and legitimacy, can be read as a set of recommendations to researchers wishing to develop policy-relevant projects based on bundles: the conceptual, strategical, and instrumental uses described in the thesis should provide ideas for such projects.

Future work around the identification and analysis of bundles (Chapter 6) should build upon on advances in the valuation of urban ES, which is a fast-growing field of research. It should also include some evaluation of uncertainties, at a depth commensurate with the intended utilisation of bundle results. Additionally, two avenues of research would constitute a substantial progress in the study of ES associations: exploring bundles across scales and investigating them in cities with contrasting morphologies.

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Appendix A

Methodology of the systematic literature review on ES bundles

A.1 Identifying relevant publications

A.1.1 Scope

The aim of this element of the literature search was to find publications detecting bundles of ecosystem services Raudsepp-Hearne sensu - i.e. patterns of ecosystem services consistently appearing either across space and/or time (bundles of supply) or across individuals as declared preferences or uses (bundles of demand and/or flow). In order to achieve this, we focused the search on peer-reviewed papers featuring adequate statistical methods to identify bundles – i.e. papers quantitatively looking for consistency, and not merely static or qualitative associations of ecosystem services. Since the first study using such methods to detect statistical associations between (more than two) ecosystem services was done by Raudsepp-Hearne et al. (2010), I covered articles spanning from this date to June 2018.

A.1.2 Online search

The search was performed on the ISI Web of Science database in June 2018 using a keyword combination with Boolean operators (see below). The combination was applied to the title/themes/abstracts of the publications in the database, and covers all material since and including 2010.

The choice of keyword combination was based on the thematic scope outlined above and designed to ensure the search was not too broad or too restrictive. We included the keyword "ecosystem AND service* AND bundl*" which was previously used for the broad search on bundle discourses, knowing that output papers referring to bundles in an out-of-scope sense would have to be excluded. We recognised that some papers may apply a bundle approach without having any mention of the term "bundl*" in their title or abstract; therefore, we tested keywords with synonyms of bundle: "ecosystem AND service* AND (group* OR cluster*"). This keyword resulted in more than 10,000 results, suggesting that the search was too broad. To restrict the results, we used the synonyms in combination with the term "trade-off*" or "tradeoff*" or "synerg*". Additionally, to avoid missing relevant papers which do not mention either bundles or their synonyms in combination with trade-offs, we included terms related to the methods used for bundling, as described in Mouchet et al. (2014). The logic behind the construction of the keyword chain is summarised in Figure A.1 below.

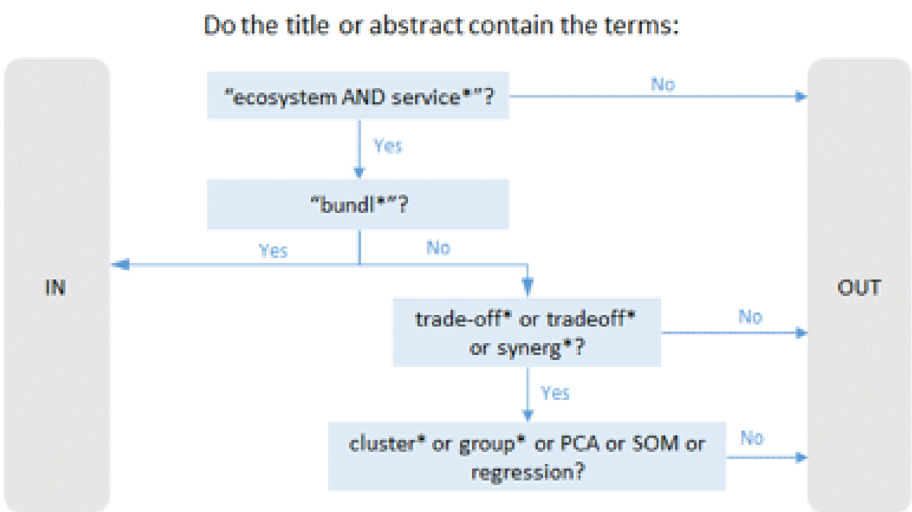

Figure A.1: Schematic representation of the keyword loop. Each separation represents an 'OR' and each vertical line an AND.

The combination is:

(ecosystem AND service) AND (bundl* OR ((trade-off* OR tradeoff* OR synerg*) AND (group* OR cluster* OR PCA OR SOM OR regression)))*

A.1.3 Establishment of the database of bundle papers

The database of bundle papers was built in three steps from the search results:

- Step 1: Screening of titles to exclude any publications clearly out-of-scope (e.g. not related to ecosystem services at all);
- Step 2: Screening of abstracts to exclude any other out-of-scope publications for which analysis based on the title was inconclusive; and
- Step 3: Selection of relevant papers based on the paper content.

A.2 Collating information

Reporting and analysis was done in Excel.

A.2.1 Identification of papers

The title, authors, journal and date of publication were reported. Each paper was attributed an identification code, as follows: [Name of first author][Date of publication]. The geographical scope of the studies was also included: location where the assessment was done and scale (resolution) of the assessment.

A.2.2 Ecosystem services included in the assessment

A list of all ecosystem services assessed and bundled in each respective paper was noted and the following information reported for all of them:

- Name of service as defined in the paper;

- Paper ID code;
- Indicator used in the paper to measure the service;
- Category of the service according the Common International Classification of Ecosystem Services (CICES) (provisioning, regulating, cultural);
- Whether the indicator measure the potential, flow or demand of the service.

The last two pieces of information above were deduced from data provided in the papers.

A.2.3 Characteristics of the bundles detected

Each bundle was recorded with its name and description as given in the relevant paper. The type of bundle (supply, demand or supply/demand) was specified, as well as the methods used to identify and analyse them.

A.3 Analysis

Three sets of analyses were performed.

1. Exploration of the state of research with an interest in bundles:
   (a) Yearly rate of publication of bundle papers;
   (b) Analysis of the number of ecosystem services included in bundling exercises, by type of bundle (supply / demand): range; average; proportion of provisioning, regulating and cultural services.
   (c) Identifying which statistical methods are preferred for the detection of bundles and the identification of their drivers; as well as which complementary analyses are done to enrich bundle detection through, for example determining the strength of associations between ecosystem

services, identifying hotspots / cold spots, calculating uncertainties, etc.

2. Analysis of the influence of scale and landscape pattern on the detection of bundles, based on the results of studies which included analysis of these issues.

3. Analysis of how assessments with bundles answer the following questions, based on the interpretation of bundles by the authors who detected them:

   (a) What are the relationships between ecosystem services, from the supply and/or the demand sides, across space, time and/or stakeholder groups?

   (b) Which socio-ecological conditions influence these relationships? and

   (c) Which type of policies or planning strategies could be informed by bundles and how?

Appendix B

Correspondence between spatial data categories and map products attributes

Table B.1: Correspondence between spatial data categories and map products attributes

Greenspace Feature	Map Product	Relevant attributes	Corresponding attribute values
Trees	OS MasterMap Topography Layer: Area	Descriptive Term	Term starting with 'Coniferous Trees' or 'Nonconiferous Trees' or 'Orchard'
	OS MasterMap Topography Layer: Point	Descriptive Term	Term starting with 'Positioned Trees'

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Greenspace Feature	**Map Product**	**Relevant attributes**	**Corresponding attribute values**
Grass (rough)	OS MasterMap Topography Layer: Area	Descriptive Term	Term starting with 'Rough Grassland'
Grass (mowed)	OS MasterMap Topography Layer: Area	Descriptive Group, Make, Descriptive Term	Group is ('General Surface' or 'Rail' or 'Rail, Structure' or 'Roadside' or Roadside, Structure) and Make is 'Natural' and Term is Null
Scrub	OS MasterMap Topography Layer: Area	Descriptive Term	Term starts with 'Scrub' or 'Heath'
Rivers/ Canals[a]	OS MasterMap Topography Layer: Area	Descriptive Group, ShapeArea, ShapeLength	Group starts with 'Inland Water' and polygon has a Polsby-Pepper score lower than or equal to 0.25

continued . . .

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Greenspace Feature	Map Product	Relevant attributes	Corresponding attribute values
Ponds/ Reservoirs[a]	OS MasterMap Topography Layer: Area	Descriptive Group, ShapeArea, ShapeLength	Group starts with 'Inland Water' and polygon has a Polsby-Pepper score greater than 0.25
Agricultural Fields	OS MasterMap Topography Layer: Area	Descriptive Term	Term is 'Agricultural Land'
Urban Growing Spaces	OS MasterMap Greenspace	priFunc	Primary function starting with 'Allotment'
Private Gardens	OS MasterMap Greenspace	priFunc	Primary function is 'Private Gardens'
Institutional Grounds	OS MasterMap Greenspace	priFunc	Primary function is 'Institutional Grounds', 'Religious Grounds' or 'School Grounds'

continued . . .

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Greenspace Feature	**Map Product**	**Relevant attributes**	**Corresponding attribute values**
Parks	OS MasterMap Greenspace	priFunc	Primary function is ’Public Parks or Gardens’
Cemeteries	OS MasterMap Greenspace	priFunc	Primary function is ’Cemeteries’
Sport	OS MasterMap Greenspace	priFunc	Primary function is ’Golf Course’, ’Playing Field’, ’Tennis Court’, ’Other Sports Facility’ or ’Bowling Green’
Playing Spaces	OS MasterMap Greenspace	priFunc	Primary function is ’Play Space’

[a] The Polsby-Popper score pp measures the degree of compactness of a polygon on a scale of 0 to 1, with a line having a score of 0 and a circle a score of 1: $pp = 4\pi\frac{Area}{Perimeter^2}$. The cut-off value of 0.25 to differentiate linear water features from non-linear ones was selected in accordance with eftec (2018*a*).

Appendix C

Details on the methodology for quantifying individual services

C.1 Air purification

C.1.1 Indicator

The deposition of atmospheric pollutants into vegetation can be reflected by two indicators: the deposition velocity ($m.s^{-1}$) or the capture rate ($g.m^{-2}.yr^{-1}$) of a given pollutant. The deposition velocity relates to the *capacity* of vegetation to remove the pollutant, while the capture rate measures the *flow* of removal considering the pollutant's concentration. Because concentration is known to influence the amount of pollutant intercepted by vegetation (Davies et al. 2011), capture rates were preferred over deposition velocities.

Vegetation captures a wide range of atmospheric pollutants, such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter less than 10 μm (PM_{10}). The study focuses on PM_{10} following the rationale laid out by Derkzen et al. (2015), arguing that this pollutant is one of the most effectively removed pollutants and also one of the most harmful to human health.

Indicator selected for Air Purification: Capture rate of PM_{10} ($g.m^{-2}.yr^{-1}$)

C.1.2 Development of the methodology

The relevant spatial data to consider is, given the biophysical processes underlying the capture of airborne particles by green spaces:

- The Vegetation Class (Trees, Scrub, Grass);
- The Private Gardens Feature;
- The distance to Major Roads as a proxy for the influence of particles concentration on their capture by vegetation.

The capture of PM_{10} by **trees and grass** in British urban areas has been assessed as part of the development of the National Ecosystem Accounts (Jones et al. 2017). Estimates were obtained using the EMEP4UK model [1] for the year 2015 and are reported as a total across all British urban areas. An average capture rate was derived using the reported total area of each type of greenspace (Table C.1):

Table C.1: Deriving air purification values for trees and grass. The calculated data is indicated in bold.

Greenspace feature	Total area across urban UK (ha)	Amount of PM_{10} captured across urban UK ($kt.yr^{-1}$)	**Amount of $\mathbf{PM_{10}}$ captured per area unit ($\mathbf{g.m^{-2}.yr^{-1}}$)**
Trees	99,400	4.38	**4.41**
Grass[a]	420,400	0.07	**0.02**

[a] No distinction between rough and mowed.

The value for **scrub** was derived from two studies reporting capture rates for shrubs in Santiago de Chile (Escobedo & Nowak 2009) and Mexico City (Baumgardner et al. 2012). Following Derzen et al.'s the methodology, the average values calculated from the two studies were adjusted to the British context considering the difference between the tree value for the UK and the tree values from Santiago and Mexico City (Derkzen

[1]see Annex for a description of EMEP4UK.

et al. 2015).

Baumgardner et al. (2012) modelled PM_{10} capture by trees and shrubs in a Mexican peri-urban forest using pollution concentration data, modeled meteorological and pollution variables, and measured forest structure data. Table C.2 shows the values reported for each ecosystem and the calculated means of these values:

Table C.2: Capture rates for PM_{10} in different ecosystems of a Mexican peri-urban forest ($g.m^{-2}.yr^{-1}$) and means calculated across the ecosystems Baumgardner et al. (2012). Calculated data is in italics.

Ecosystem	Tree	Shrub
Agricultural/A.religiosa	10.13	14.3
A. religiosa Forest	7.13	1.45
P.hartwegii-WestForest	5.95	6.6
P.hartwegii-EastForest	6.6	0.73
High alpine meadow	0.57	0.54
Mean	*6.08*	*0.96*

Escobedo & Nowak (2009) modelled PM_{10} capture by trees and shrubs in three socioeconomic subregions in Santiago de Chile using measured urban forest structure, data hourly climate, mixing height, and pollutant concentration data. Table C.3 shows the values reported for each subregion as well as vegetation structure data. Calculated means are also reported.

Table C.3: Capture rates for PM_{10} in different subregions of Santiago, Chile ($g.m^{-2}.yr^{-1}$) and field data used to calculate means across the subregions Escobedo & Nowak (2009). Calculated data is also reported, in italics.

	Subregion: "Low"		Subregion: "Medium"		Subregion: "High"	
	Trees	Shrubs	Trees	Shrubs	Trees	Shrubs
Number of plots	64		62		74	
Size of plots (m^2)	4000		4000		4000	
Cover (%)	13.7	8.0	12.2	9.8	25.9	15.9
Capture rate ($g.m^{-2}.yr^{-1}$)	-	5.8	7.4	5.7	7.5	8.5
			Trees		Shrubs	
Mean capture rate across the three subregions ($g.m^{-2}.yr^{-1}$)			*7.47*		*7.16*	

The final estimation for scrub is obtained by applying the ratio between the calculated tree values and the one previously obtained for the UK (Table C.4).

Table C.4: Summary of mean PM_{10} capture rates for trees and shrubs in Mexico City and Santiago de Chile, and derivation of a scrub value for the model ($g.m^{-2}.yr^{-1}$). Newly calculated data is reported in bold.

Location	Trees	Shrubs
Mexico City	6.08	0.96
Santiago de Chile	7.47	7.16
United Kingdom	4.41	**2.64**

The value for **private gardens** was derived from the previously calculated values for trees, grass and scrub by applying the proportion of each greenspace feature (Table C.5).

Table C.5: Estimation of the PM_{10} capture rate for Private Gardens ($g.m^{-2}.yr^{-1}$). Newly calculated data is reported in bold.

Greenspace Feature	Proportion in Private Gardens	PM_{10} capture rate ($g.m^{-2}.yr^{-1}$)
Trees	0.09	4.41
Grass	0.38	0.02
Scrub	0.11	2.64
Private Garden	**-**	**0.69**

Following the methodology developed by Derkzen et al. (2015) to take into account the **influence of particles' concentration on the air purification service**, the values reported in Table C.5 were multiplied by 2 in a 50m buffer around major roads.

The model assigns the values calculated here to each relevant spatial object, then performs an aggregation at the data zone scale by calculating the average capture rate weighted by the areas of each greenspace feature in the data zone.

C.1.3 Limitations and Uncertainties

Limitations to the accuracy of the estimations made for the models are:

- The assessment does not take into account site-specific meteorological conditions such as wind and temperature, even though these are included in the model used to infer the values reported in the data sources.
- The accuracy for the Scrub feature is quite low due to the data sources being from Latin American cities.
- The application of a factor 2 in a 50m-buffer around main road is a rough estimation of the influence of pollutant concentration.

In the absence of quantified uncertainties in the data source for trees and grass (Jones et al. 2017), the differences between estimations presented here and estimations obtained by Derkzen et al. (2015) were considered (Table C.6). For shrubs, means of the minimum and maximum values for the different areas studied by Baumgardner et al. (2012), Escobedo & Nowak (2009) (forest ecosystems and socioeconomic subregions, respectively) were taken as lower and upper boundaries of the uncertainty interval (Table C.6).

Table C.6: Estimation of uncertainties on the PM_{10} capture rates ($g.m^{-2}.yr^{-1}$). Newly calculated data is reported in bold.

Greenspace Feature	Value in Derkzen et al. (2015)	Min - Max in Baumgardner et al. (2012)	Min - Max in Escobedo & Nowak (2009)	Uncertainty interval (Low Scenario, High Scenario)
Trees	3.97	N/A	N/A	(3.97, 4.85)
Grass	0.9	N/A	N/A	(0, 0.9)
Scrub	N/A	0.54 - 1.45	2.79 - 11.17	(1.08, 4.11)[a]
Private Garden	N/A	N/A	N/A	(0.48, 0.9)[b]

[a] The ratio between the values for trees estimated for the model and the values from (Baumgardner et al. 2012, Escobedo & Nowak 2009) was applied.
[b] The uncertainty interval is obtained using the proportion of each vegetation feature class.

C.2 Noise attenuation

C.2.1 Indicator

The indicator for noise attenuation is the reduction of sound pressure level due to the presence of natural elements, as perceived by the human ear. This indicator is consistent with standards for environmental noise, which use sound pressure levels with a frequency-dependent correction to approximate the human ear's sensitivity to sound (refs). The literature on the noise attenuation ecosystem service also use this indicator and unit (eftec 2018*b*).

C.2.2 Development of the methodology

A methodology for assessing the noise attenuation service in urban areas in the UK was developed by eftec and CEH for the Natural Capital Accounts (eftec 2018*b*). Based on a literature review, the authors estimated the levels of noise reduction provided by patches of woodland of different sizes (only trees provide a significant contribution to noise attenuation):

- Larger patches (>3,000m2) of woodland are associated with a 2dBA reduction in noise
- Smaller patches of woodland (<3,000m2) provide a lower service: 1dBA reduction
- Very small patches of woodland (<200m2) and individual street trees do not provide any service

I applied a modified version of this methodology:

- I used the "Trees" feature and not woodlands to identify relevant patches.
- I added the influence of the proximity to noise sources by:
  - Applying a buffer of 50m around main roads (Derkzen);
  - Applying a factor 2 to the noise reduction levels provided by tree patches within the buffer. The choice of a factor 2 was based on the maximum values found in the literature by (eftec 2018*b*).

Because noise is an intensive property, the average value of noise attenuation across a data zone cannot be calculated. The 'expected value' measure is used instead: let's assume that one picks a random point in a specific data zone – the probability of falling into a specific greenspace feature, and therefore of benefiting of a specific noise attenuation value, is:

$$p_{feature} = \frac{A_{feature}}{A_{DataZone}}.$$

One can then define the expected value of noise attenuation across the data zone by:

$$\sum_{All\ features\ in\ the\ data\ zone} \Delta NoiseAttenuation_{feature} \cdot p_{feature}.$$

C.2.3 Limitations and Uncertainties

There are numerous conditions affecting the level of noise attenuation provided by urban vegetation, of which the methodology only considers two. For instance, neither the structure of tree patches nor the types and size of trees or their planting density, were included. Furthermore, the influence of noise levels was crudely estimated with a factor 2 due to the lack of studies comparing the performance of similar patches located a different distances of noise sources. The 50m-buffer where this factor was applied is also an estimation which could have been refined by using noise level mapping https://noise.environment.gov.scot/

C.3 Carbon Storage

C.3.1 Indicator

Carbon storage refers to the amount of carbon stored in vegetation and soils. Although urban soils can stock carbon at a similar or higher density than rural or forest soils ((Raciti et al. 2012)), their mixed and disturbed nature makes their quantification complex and subject to high uncertainties (Derkzen et al. 2015). I am therefore following Derkzen et al. (2015) and others in excluding soils from the assessment. Similarly, below-ground biomass has been shown to potentially store large amount of carbon in urban areas (Jo & McPherson 1995), but the high variability of reported values hinders the quantification of this pool. I am therefore following the approach of Strohbach & Haase (2012) in remove it from the assessment. The conservative approach adopted here, which excludes soils and below-ground biomass, is likely to lead to an underestimation of the carbon storage ES.

The indicator for carbon storage in this study is the density of carbon stored in above-ground biomass ($kg.m^{-2}$).

C.3.2 Development of the methodology

C.3.2.1 Carbon stored by trees

The City of Edinburgh assessed the carbon storage value of its trees in 2011, with an update in 2017 (ref), using the i-Tree Eco model. The investigators collected data from a stratified sample of 200 plots across the city (within the ring road), such as: the number of trees, their species, their height, their canopy spread - the complete list of parameters is available in the report referenced above. Outputs from the model include the amount of carbon stored by species and in total across the city.

Because spatial data used in this study did not specify tree characteristics such as their species or condition, I used the total amount of carbon stored across the city: the assessment reports 179,237 tonnes for a canopy cover of 1,950 ha, which gives an average density of $9.19 kg.m^{-2}$. This value is likely to be an underestimation due to the inclusion of shrubs in addition to trees in the i-Tree study's scope.

The density assigned to trees in this methodology is consistent with the literature reviewed in Derkzen et al. (2015) as well as with more recent assessments (Tang et al.

2016, Neto & Sarmento 2019).

C.3.2.2 Carbon stored by shrubs

Two studies assessing the amount of carbon stored by shrubs were found, conducted in Leicester (Davies et al. 2011) and Leipzig (Strohbach & Haase 2012). The study in Leicester also reported a carbon density value for trees, which amounted to $29kg.m^{-2}$. The discrepancy between this value and the one estimated for Edinburgh, in addition to the fact that the amount for scrubs was three times the value reported in Leipzig, prompted me to follow the approach of Derkzen et al. (2015) to correct the Leicester value: I adjusted it based on the ratio between the values for trees derived above and the one reported in Davies et al. (2011). The application of This ratio of 0.33 resulted in an adjusted value consistent with density reported in Leipzig. The mean of the two values gave the estimate used in this methodology: $2.27kg.m^{-2}$

C.3.2.3 Carbon stored by grass

Only one study was found, which reports the density of carbon stored by grass (Davies et al. 2011): their value of $0.14kg.m^{-2}$ was used. This study has been shown to overestimate amounts for both trees and scrubs, but no adjustment was done for grass due to the lack of comparable data.

C.3.2.4 Carbon stored by private gardens

The value for private gardens was derived from the previously calculated values for trees, grass and scrub by applying the proportion of each greenspace feature (Table C.5). This gives an estimate of $1.08kg.m^{-2}$.

C.3.3 Limitations and uncertainties

C.3.3.1 Errors in estimating the amount of carbon stored by trees

Two sources of errors can be identified:

- Sampling error from the i-Tree eco assessment
- Assumed linearity between canopy cover and amount of stored carbon, in the absence of spatial data regarding other parameters

Both errors were addressed using standard errors provided in the i-Tree report, as detailed thereafter.

The i-Tree Eco plot-sample type projects use traditional stratified sampling, wherein the sampling error is estimated by calculating the standard deviation of the mean across samples, i.e. the so-called standard error of the mean (SEM) [2]. The i-Tree report does not provide an overall SEM but specifies SEM values for each of the ten tree species with the highest storage rates, along with the amount of carbon stored and the frequency of each species. This provided the opportunity to derive the error due to assuming linearity between canopy cover and amount of stored carbon across different tree species.

An approximation of the error around the estimated carbon density $d_0 = 9.19 kg.m^{-2}$ was calculated using the following method:

First, $SEM(d_i)$ of the carbon density d_i stored by each species sp_i was estimated:

$$SEM^2(d_i) = SEM^2\left(\frac{C_i}{A_i}\right)$$

where C_i is the amount of carbon stored by species i and A_i the area covered by species i. C_i values were collected from Figure C.1 and A_i was estimated using the number of

[2] $(https://www.itreetools.org/documents/636/sample_variance.pdf)$

trees N_i reported in Figure C.1, the total number N of trees across the city and the total canopy cover A: $A_i = A.\frac{N_i}{N}$.

$SEM^2\left(\frac{C_i}{A_i}\right)$ can be estimated using a second degree Taylor expansion [3]:

$$SEM^2\left(\frac{C_i}{A_i}\right) = \left(\frac{\mu_{C_i}}{\mu_{A_i}}\right)^2 . \left(\frac{SEM^2(C_i)}{\mu_{C_i}^2} - 2.\frac{Cov(C_i, A_i)}{\mu_{C_i}\mu_{A_i}} + \frac{SEM^2(A_i)}{\mu_{A_i}^2}\right)$$

C_i and A_i were considered to be proportional, which is a simplification ignoring the role of parameters such as size or condition. The assumption of proportionality led to estimating $Cov(C_i, A_i)$ using d_0:

$$Cov(C_i, A_i) = E(C_iA_i) - E(C_i)E(A_i) = \frac{1}{d_0}\left(E({C_i}^2) - E(C_i)^2\right) = \frac{1}{d_0}Var(C_i)$$

With $Var(C_i) = N_{sample}.SEM(C_i)^2$, where $N_{sample} = 200$, as reported in the i-Tree assessment, we have:

$$Cov(C_i, A_i) = \frac{SEM^2(C_i)}{d_0 N_{sample}}$$

Finally, $SEM(d_i)^2$ can be calculated using the following formula:

$$SEM^2\left(\frac{C_i}{A_i}\right) = \left(\frac{\mu_{C_i}}{\mu_{A_i}}\right)^2 . \left(\frac{SEM^2(C_i)}{\mu_{C_i}^2} - 2.\frac{SEM^2(C_i)}{d_0 N_s ample \mu_{C_i}\mu_{A_i}} + \frac{SEM^2(A_i)}{\mu_{A_i}^2}\right)$$

The application of this formula showed that the tree species with the most variability (Poplar spp, sweet chestnut and Lawson's cypress) had their SEM^2 higher than their carbon density squared, indicating that they did not fall into the domain of validity of the Taylor expansion. The impact on the final estimation of SEM(d) was tested by

[3] http://www.stat.cmu.edu/ hseltman/files/ratio.pdf

removing the three species and comparing the outcome with the result obtained below using all species: the difference was 0.1%, which was considered small and all species were therefore kept.

The SEM across the 10 top tree species is:

$$SEM(d) = \sqrt{\frac{\sum_i {A_i}^2 SEM^2(d_i)^2}{\sum_i {A_i}^2}}$$

The application of this formula led to the result:

$$SEM(d) = 3.5kg.m^{-2}$$

This estimation does not take into account the variability due to other parameters such as tree size or condition.

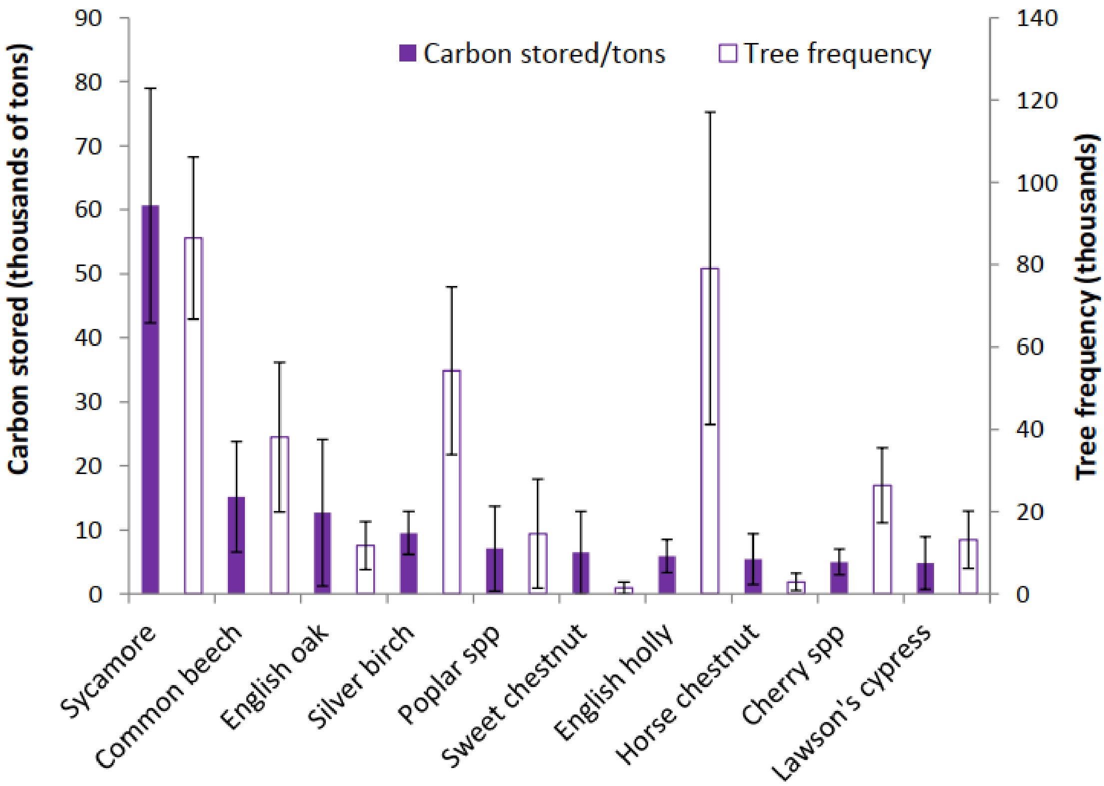


Figure C.1: Amount of carbon stored in the Edinburgh trees and the frequency of each species. Only the ten trees with the highest storage rates are displayed. Error bars denote standard error of the mean (SEM). Reproduced from Doick et al. (2017).

C.3.3.2 Errors in estimating the amount of carbon stored by shrubs

The studies in Leipzig and Leicester both reported the error around the reported values. The squared error of the mean of two independent variables is:

$$
\begin{aligned}
SEM_{shrubs} &= SEM\left(\frac{C_{Leicester} + C_{Leipzig}}{2}\right) \\
&= \sqrt{SEM^2\left(\frac{C_{Leicester}}{2}\right) + SEM^2\left(\frac{C_{Leipzig}}{2}\right)} \\
&= \sqrt{\frac{1}{4}SEM^2(C_{Leicester}) + \frac{1}{4}SEM^2(C_{Leipzig})} \\
&= \frac{1}{2}\sqrt{SEM^2(C_{Leicester}) + SEM^2(C_{Leipzig})}
\end{aligned}
$$

The application of the formula to the values reported in the studies led to the result:

$$SEM_{shrubs} = 0.35kg.m^{-2}$$

C.3.3.3 Errors in estimating the amount of carbon stored by grass

The error reported in the study in Leicester is:

$$SEM_{grass} = 0.01kg.m^{-2}$$

C.3.3.4 Errors in estimating the amount of carbon stored by private gardens

Using the proportion of a garden's land use types pi and the error Ei associated with their estimated carbon density:

$$SEM_{gardens} = \sqrt{\sum_i {p_i}^2 {SEM_i}^2}$$

The application of the formula to the values reported in the studies led to the result:

$$SEM_{gardens} = 0.32kg.m^{-2}$$

C.4 Temperature Regulation

C.4.1 Indicator

The indicator selected is directly the difference in air temperature due to vegetation and water cover, in degrees Celsius.

C.4.2 Development of the methodology

The relevant spatial data to consider is, given the biophysical processes underlying the capture of airborne particles by green spaces:

- The Vegetation Class (Trees, Scrub, Grass);
- The Private Gardens feature;
- The Water Class (Rivers/Canals and Ponds/Reservoirs).

The cooling properties of British urban green spaces have been assessed as part of the development of the National Ecosystem Accounts (eftec 2018*a*). Estimates were determined with an evidence review from available literature and are reported in Table C.7 using the project's classification of greenspace types.

Table C.7: Temperature reduction associated with the different relevant Greenspace Features. Adapted from eftec (2018*a*).

Greenspace Feature	Condition	Temperature differential in feature (°C)	Size of buffer (m)	Temperature differential in buffer (°C)
Rivers/Canals	Width $\geq$ 25m	-1.4	30	-0.8
Ponds/Reservoirs	Area $\geq 700\ m^2$	-0.1	30	-0.057
Trees[a]	$200m^2 \leq$ Area $<$ $30{,}000m^2$	-3.5	-	-
	Area $\geq$ $30{,}000m^2$	-3.5	100	-0.52
Scrub and Grass[b]	Area $\geq 200m^2$	-0.95	-	-
Private gardens (contiguous)[c]	Area $\geq 200m^2$	-0.95	-	-

[a] Originally "Woodland".
[b] Originally "Open Parks and Grass".
[c] Contiguous gardens are amalgamated in order to only include composite areas large enough to provide a service.

The temperature reduction value for a data zone can be defined by its expected value across the zone [4]:

Let's assume that one picks a random point in a specific data zone. The probability of falling into a specific greenspace feature, and therefore of benefiting of a specific temperature reduction value, is:

$$p_{feature} = \frac{A_{feature}}{A_{DataZone}}.$$

[4] We cannot talk about weighted average here, given that temperature is an intensive property.

One can then define the expected value of temperature reduction across the zone by:

$$\sum_{All\ features\ in\ the\ data\ zone} \Delta T_{feature} \cdot p_{feature}.$$

C.4.3 Limitations and Uncertainties

Giving the limited empirical evidence in the UK, it was not possible to identify a range of values in which the temperature reduction service of each feature type may fall. The values used in the model are rough estimations of the temperature differentials between a sealed and a green space.

Furthermore, the influence of the actual air temperature in Edinburgh, as well as the influence of building density, were not considered in the assessment.

C.5 Run-off retention

C.5.1 Indicator

The indicator selected is the amount of water run-off retained after a storm event, in $L.m^{-2}$.

C.5.2 Development of the model

Volumes of run-off retained by different types of urban land covers were calculated using the method developed by (Whitford et al. 2001) on the basis of studies conducted by the US Soil Conservation Service (now the US National Resources Conservation Service) (Soil Conservation Service 1972, Pandit & Gopalakrishnan 1996). This method was used by (Tratalos et al. 2007) to quantify run-off retention in five UK cities, and forms the core of the "Urban Flood Risk Mitigation" model developed by the Natural Capital project (Natural Capital Project 2019).

The method calculates run-off retention R (mm) as:

$$R = P - P_e$$

Where P is the precipitation for a typical storm event (mm) and P_e the surface run-off (mm):

$$P_e = \frac{(P - 0.2 * S)^2}{P + 0.8 * S}$$

Where S is the maximum potential rainfall retention (mm). S is a function of the so-called Curve Number CN, an empirical parameter defined by the US National Resources Conservation Service that depends on land use and soil characteristics (USDA-NRCS 2004):

$$S = \frac{2540}{CN - 25.4}$$

In this thesis, CNs were determined for each of the relevant land cover types defined in Chapter 3: Tree, Scrub, Grass (mowed), Rough grassland, Other unsealed, Sealed, Agriculture. For all types but agriculture, the CNs determined by (Tratalos et al. 2007) were used. The authors assumed the same soil types across all land covers: sandy loam of hydrological group B. This hydrological group characterises soils with moderately low runoff potential when thoroughly wet (USDA-NRCS 2009), and the authors identified sandy loam as a common soil type. CN values calculated by the authors and used in this thesis are reported in Table C.8, which also indicates the cover description corresponding to these values, as deducted from from the NRCS handbook (USDA-NRCS 2004).

Table C.8: Curve Numbers for different types of land covers

Land cover	CN reported in Tratalos et al. (2007)	Corresponding combination of cover type and hydrological soil condition in the USDA-NRCS (2004)
Tree	55	Woods: Good condition
Scrub	66	Woods: Poor condition
Grass (mowed)	61	Grassland: Good condition
Rough grassland	58	Meadow: Good condition
Other unsealed	74	Mean of gravel and dirt

The CN for Private Gardens was calculated using the typical composition determined in Chapter 3: $CN_{PrivateGardens} = 74.5$. CNs are not defined for water: a surface run-off of zero is assumed for water features.

For agricultural cover types, CNs were derived directly from the NRCS handbook (USDA-NRCS 2004). Because CN depends on the hydrologic soil group, hydrologic soil conditions and cover type, it was necessary to determine these parameters first:

- Cover type: 75% of the agricultural land in the City of Edinburgh Council (Figure 3.1) is used for arable and vegetable crops, the major one being barley (The City of Edinburgh Council n.d.). The rest is being used as grazing land. However, no spatial data assigning these different uses to agricultural land cover was found: as a result, the dominant use (crop growing) was assigned to all spatial features classified under the "Agricultural Land" Descriptive Term in the OS Topography MasterMap, corresponding to the "Small grain" cover type of the NCRS handbook.
- Hydrologic soil group and hydrologic soil condition: these parameters were

derived from data on the compaction class of Scottish soils, as detailed below.

Lilly & Baggaley (2014) assigned a compaction class to Scottish soils based on their texture and drainage classes. The compaction classification has three levels: Low, Moderate and High. The combination of texture and drainage that leads to each of these levels is reported in Table C.11. In order to derive CNs for each compaction class, correspondence with parameters from the NRCS handbook were made:

- Drainage classes defined by the authors can easily be compared to the hydrological condition categories used by the NCRS: as a result, a correspondence between the two classifications was made based on their descriptions (Table C.9).
- Texture classes used by the authors correspond directly to the hydrological soil groups defined by the NRCS (Table C.10).

Table C.9: Correspondence between Natural Soil Drainage Class, Drainage subgroup, and Hydrological Soil Condition

Natural Soil Drainage Class	Drainage subgroup (Lilly & Baggaley 2014)	Hydrological Soil Condition (USDA-NRCS 2004)
Free and Excessive	1	Good: average and better then average infiltration
Imperfect	2	Good: average and better then average infiltration
Poor	3	Poor: impaired infiltration
Very poor	3	Poor: impaired infiltration
Free below pan	3	Poor: impaired infiltration

Table C.10: Compaction subclass based on soil texture

Texture Class	Compaction subclass (Lilly & Baggaley 2014) / Hydrological soil group (USDA-NRCS 2009)
Sandy loam, Loam	A
Sandy loam (OM<5%), Loamy sand, Silty loam	B
Sandy clay loam, clay loam, Silty clay loam, Silty clay	C

Table C.11: Compaction class for different combinations of texture and drainage (Lilly & Baggaley 2014)

Combined class (texture & drainage)	Compaction class
A1	Low
A2, B1, B2	Moderate
A3, B3, C2, C3	High

In order to assign a CN to each of the three levels of compaction defined by (Lilly & Baggaley 2014), I calculated CNs for each of the relevant combinations of hydrological condition and hydrological soil group, from values reported in Table 9-1 of USDA-NRCS (2004) for the "small grain" cover type (Table C.12). USDA-NRCS (2004) defines different CNs for different so-called "treatments" (straight rows, contoured, etc.): the mean of values across all treatment types was used.

Table C.12: Mean of soil CN values across different treatments for the "small grain" cover type, broken down by hydrological condition and hydrological group

	Hydrological group			
Hydrologic condition	A	B	C	D
Poor	62	73	81	84
Good	60.3	72	80	83.7

CNs were then determined using the correspondences reported in Table C.9 and Table C.10:

Table C.13: CNs for each compaction class

Compaction Class	CN	Corresponding combination of hydrological group and condition
Low	60.3	A-good
Moderate	66.2	A-good; B-good (mean)
High	74	A-poor; B-poor; C-good; C-poor

Each agricultural patch is then attributed a CN equal to the mean of the CNs of the different soil types that compose it.

The run-off retention rates were then calculated from the CNs determined here (Table C.8 and C.13), and using a typical UK storm event of $P = 12mm$ following Whitford et al. (2001) and Tratalos et al. (2007). Rates are reported in the main document (section 3.4.2.2), with the conversion of $1mm$ precipitation corresponding to $1L.m^{-2}$.

C.5.3 Limitations

There are several sources of uncertainties in the assessment of the run-off retention service, including:

- Assigning the same type of soil (type B sandy loam) to all locations of land cover types other than agriculture;
- Not distinguishing between different agricultural land uses;
- Using a typical UK storm event which may not reflect rainfall in Edinburgh;
- Not taking into account topographical features such as slope or the potential presence of engineered features that could influence retention.

In order to estimate the level of uncertainty introduced by the methodology, I studied the impact of the first and second sources of uncertainty listed above. For the first source of uncertainty, I considered CNs associated with soils at each end of the hydrological soil group classification (USDA-NRCS 2009).:

- Group A, corresponding to soils through which water is transmitted freely; and
- Group D, corresponding to soils through which water movement is restricted or very restricted.

I calculated retention rates corresponding to the CNs of these groups, with Group A corresponding to the upper bound of the value range and Group D to the lower bound (Table C.14).

For the agricultural land cover, I estimated the range of retention values for each compaction class by considering the minimal and maximal values of CN across the crop cover types listed in USDA-NRCS (2004) (fallow, row crops, small grain, Close-seeded or broadcast legumes). I selected the minima and maxima corresponding to the texture / drainage combination of each compaction class (Table C.14):

Table C.14: Minimum and maximum CN for each land cover (USDA-NRCS 2004)

Land cover	Characteristics of minimum CN (cover-group-condition)	min CN	Characteristics of maximum CN (cover-group-condition)	max CN
Tree	woods-A-good	30	woods-D-good	77
Scrub	woods-A-poor	45	woods-D-poor	83
Grass (mowed)	grassland-A-good	39	grassland-D-good	80
Rough grassland	grassland-A-good	30	grassland-D-good	78
Other unsealed	gravel-A	30	dirt-A	78
Sealed	Paved impervious areas	98	Paved impervious areas	98
Private gardens	Linear combination of tree, scrub, grass (mowed), rough grassland, other sealed, sealed	30	dirt-A	78
Agricultural land - Low compaction	min All covers-A-good	53	max All covers-A-good	63
Agricultural land - Moderate compaction	max All covers-A-good	63	max All covers-B-good	75
Agricultural land - High compaction	min All covers-A-poor	60	max All covers-C-poor	84

The ranges of values are reported in section 3.4.2.2.

C.6 Habitat provision

C.6.1 Indicator

The indicator is a 1-5 score representing both the extent of habitat and its richness.

C.6.2 Development of the methodology

Habitat provision was estimated using the Integrated Habitat Network maps available for the Central Scotland Green Network area (Scottish Natural Heritage 2013*b*). The maps represent habitats, as well as connecting non-habitat land providing structural connections and/or functional connectivity. The maps show the results of a modelling study based on land cover data available in 2011. Five habitat networks have been modelled:

- broadleaved woodland
- wetland (fen marsh swamp only)
- neutral grassland
- acid grassland
- heathland

Scottish Natural Heritage (2013*a*) lists the main factors influencing the value or importance of a network:

- Generally, large networks are of higher value or importance than small networks;
- Networks that incorporate designated sites or other high quality habitat have a higher value than ones that do not;

- A network (or part of) which overlays another network(s) has a greater ecosystem function and has a higher importance;
- Thin networks, in general, have less value than fatter ones – although some high quality habitats may be narrow (e.g. riparian woodland, flower-rich headlands).

The assessment of habitat provision in this thesis focuses on the level of ecosystem function provided by the overlap of different networks (third factor above). Pieces of network are given a score of 1 to 5 depending on whether they overlap 0, 1, 2, 3 or 4 other networks, respectively. Then, a weighted average of the network areas, modulated by their scores, gives the importance of the data zone for habitat provision, measured on a scale of 1 to 5.

C.6.3 Limitations

The methodology constitutes a rough estimation of the value of habitat networks. The following aspects were not factored in:

- The differences among zone types within the networks (habitat, moderate network or high dispersal network);
- The difference in value across habitat sizes;
- The inclusion, or not, of designated sites or other high quality habitat;
- The potential non-linear variation of value when increasing the number of network overlaps.

These aspects were not considered because of the lack of available robust methods to quantify their contribution. In addition, none of the networks have been assessed for site condition, species richness, habitat quality, or national or local importance.

C.7 Food growing

C.7.1 Indicator

Land cover is used as a proxy - the indicator is the proportion of land cover dedicated to food growing.

C.7.2 Development of the methodology

The proportion of land cover of Agricultural Land and Urban Growing Spaces in each data zone was calculated from the OS Topography MasterMap and Greenspace Mastermap (respectively).

C.7.3 Limitations

The methodology is a very rough estimate of the food production service. Data gaps do not allow to consider variability in yields, impacts on household budgets or on aspects related to health and well-being.

C.8 Contribution to Mental Health

C.8.1 Indicator

The indicator is the decrease in mental distress, as assessed by the General Health Questionnaire (see below), attributable to the presence of vegetation and water.

C.8.2 Development of the methodology

The quantification of the impact of urban nature on mental health is still an emerging field of research (Krefis et al. 2018, Bratman et al. 2019). Studies have linked the level of "neighbourhood greenness" (see below) to indicators of mental health, showing significant positive associations in different contexts, including: in the general population in Europe (De Vries et al. 2013, White et al. 2013) and the US (Beyer et al. 2014), in deprived areas (Thompson et al. 2012), and in populations with major depressive disorders (Sarkar et al. 2018). Neighbourhood greenness has been assessed with indicators such as normalised difference vegetation index (NDVI) (Sarkar et al. 2018, Beyer et al. 2014), percentage of greenspace area (Thompson et al. 2012, White et al. 2013), or perceived streetscape greenery (De Vries et al. 2013). Neighbourhoods have been most often defined according to census areas such as wards and output areas in the UK (Thompson et al. 2012, White et al. 2013) and census block group in the US (Beyer et al. 2014). The quantification of mental health has also been estimated with various methods across the aforementioned studies, including self-assessment questionnaires (De Vries et al. 2013, White et al. 2013) and measurement of cortisol levels (Thompson et al. 2012).

Because of the diversity of indicators used in the literature to represent neighbourhood greenness and mental health outcomes, it was not possible to robustly draw a methodology from multiple studies in the context of this thesis. It was therefore necessary to select one study and derive a methodology from it. In addition to the criteria for study selection detailed in section 3.4.2.1, I also considered the following elements:

- Sampling of the general population as opposed to specific groups;
- Definition of neighbourhood greenness compatible with geospatial data reported in the OS MasterMaps for topography and greenspace; and
- Preference for longitudinal studies over cross-sectional studies in order to reflect causal relationships between greenness and mental health.

The study conducted by White et al. (2013) fitted these elements and scores well in the reliability scale (Figure 3.4): score of 2 for "peer-reviewed literature with British case studies". White conducted a longitudinal study using data from the British Household

Panel Survey (BHPS), a nationally representative longitudinal survey of households in the UK that was conducted annually from 1991 to 2008. The authors restricted their analysis to England as land-use data was only available there: their sample included 87,573 observations from 12,818 individuals. They used the following indicators of neighbourhood greenness and mental health outcome:

- Neighbourhood greenness: percentage of greenspace in each lower-layer super output areas (LSOAs), with greenspace defined as the "green space", "residential gardens" and "water" land covers reported in the Generalised Land Use Database (GLUD).
- Mental health outcome: mental distress was assessed using scores from the General Health Questionnaire (GHQ), a widely-used and reliable self-assessment screening tool to aid clinical diagnosis of mood disorders such as anxiety and depression. Scores ranged from 0 to 3.

The study shows that a 1% increase in greenspace proportion leads to a significant decrease of 0.0043 ± 0.0013 in the GHQ score. This result was directly used to value the Contribution to Mental Health service in this thesis, with the following geoprocessing steps:

- Step 1: a "greenspace" layer, matching the land covers considered in White, was created. It contained the vegetation and water features from the OS MasterMap Topography Layer, as well as the Private Garden features from the OS MasterMap Greenspace Layer.
- Step 2: The proportion of greenspace in each LSOA was computed and the corresponding ES value assigned.
- Step 3: The ES values were aggregated in the data zones.

C.8.3 Limitations

The pathways leading to beneficial mental health effects of green space are diverse and complex (Braubach et al. 2017*b*). They are most likely influenced by various socio-economic determinants and greenspace configuration, and not only the level of neighbourhood greenness (Krefis et al. 2018, Thompson et al. 2012, Bratman et al. 2019), which makes the valuation method adopted here a helpful but limited estimation.

C.9 Contribution to Physical Activity

C.9.1 Indicator

The indicator is the increase in QALY due to active visits to greenspace, per capita per year.

C.9.2 Development of the methodology

The contribution to physical activity has been assessed based on the number of visits to a local greenspace for physical exercise meeting UK guidelines (White et al. 2016, Environment Agency 2018). The guidelines considered here are the ones published in 2011 recommending at least 150 mins per week of moderate intensity activity in bouts of 10 minutes or more [5].

The assessment meant determining, for each data zone, the extent to which public greenspace across the city were contributing to the physical activity of residents in that data zone. The first phase of the assessment was to determine the increase in QALY due to active visits to greenspace depending on the travel time to these greenspaces. It included the following steps:

[5] https://www.gov.uk/government/publications/uk-physical-activity-guidelines, accessed January 2018. Note that the guidelines have been revised in 2020.

- Determining the average number of greenspace visits in urban areas (for any purpose, including exercise):
  As this figure was not readily available in the survey reports published by SNH and Greenspace Scotland, it was estimated using data for the whole Scotland adjusted for urban areas. First, respondents to a survey conducted for the whole of Scotland (apr 17 - may 18) reported 12.4 outdoor visits on average in the 4 weeks prior to the interview (Wilson, V. & Seddon 2018). To derive a number for urban areas specifically, I considered an indicator available for both urban Scotland and Scotland as a whole: the percentage of people visiting their greenspace at least once a week: 57% for Scotland in general (Wilson, V. & Seddon 2018) and 43% for urban Scotland (Greenspace Scotland 2018). Assuming from these figures that urban residents were 75% as likely to visit greenspaces as the population in general, I estimated that 12.4 visits to the outdoors per month for the whole of Scotland translated to an average of 9.4 visits per month for urban Scotland.

- Determining the percentage of greenspace visits meeting physical activity guidelines:
  The SNH survey mentioned above reports that 70% of adults in Scotland had used the outdoors for physical exercise in the week prior to interview, with 29% meeting the national physical activity guidelines (Wilson, V. & Seddon 2018). I am assuming from this figure that 41.4% of visits for physical exercise actually meet the exercise guidelines.

- Determining the average number of greenspace visits meeting physical activity guidelines in urban areas:
  Out of the 12.4 average monthly visits per capita in Scotland, 37% are for physical exercise (Wilson, V. & Seddon 2018). Further, 41.4% of these visits for physical exercise can be assumed to meet guidelines (see above), meaning that we

can estimate that 15.3% of all visits to be for physical activity meeting guidelines. In the absence of urban-specific data, I assumed the same percentage for urban areas, leading to average of 17.2 visits to greenspace for physical activity meeting guidelines per capita per year in urban Scotland ($9.35 \times 15.3 \times 12 = 17.2$).

- Determining the the average number of greenspace visits meeting physical activity guidelines, depending on travel time:
  The Third State of Scotland's Greenspace Report (Greenspace Scotland 2018) shows that people living closer to a public green space are more likely to visit them (in general, not necessarily for physical activity): 61% of people living 5 min from their local green space visit them once a week or more often; the rate drops to 40% for people living 5 to 10min from their local green space and to 18% for people living from 11 to 20 min away. Furthermore, on average, 43% of the population visit their local greenspace once a week or more often: this is assumed to mean that there is a probability of 0.43 that people will visit their greenspace at least once a week. Assuming this figure to correspond to an average number of 17.2 visits per year for physical activity meeting guidelines (see above), we can derive estimated number of visits per year for each travel time assuming a linear relationship: 24 visits for people living 5min from their local green space, 16 for people living 10min from their local green space and 7 for people living from 11 to 20 min away. Given the low estimated visit frequency for people living more than 11 minutes away from greenspace (bimonthly visits), I focused on the contribution to physical activity provided to people living less than 10 minutes away from greenspace.

- Determining the approximate increase in QALY depending on travel time: White et al report that 30 min a week of moderate-intense physical activity, if undertaken 52 weeks a year, is associated with and increase of 0.010677 QALY. From this figure, a single activity meeting guidelines can be associated with an increase of

2.1×10^{-4} QALY (0.010677/52). Using the number of visits meeting guidelines reported above, the increases in QALY per year per capita for each travel time are: 5×10^{-3} (<5min) and 3.2×10^{-3} (between 5 and 10min).

The second phase was to assign the QALY values determined above to relevant spatial areas. A simple approach using buffers around greenspace was applied: the main geoprocessing steps were the following:

- Creating a feature class gathering the exercise-relevant greenspace polygons from the OS Greenspace Mastermap: 'Public Park Or Garden', 'Playing Field', 'Bowling Green', 'Golf Course', 'Tennis Court'. These features will be referred to as "greenspace" in the following paragraphs.

- Converting travel times into buffers (first approximation): a <5min travel time was converted into a 400m-buffer around greenspace. The "5min-area" included the buffer and the greenspace it surrounded. A travel time from 5 to 10 minutes was converted into a 400m-buffer around the <5min buffer ("10min-area").

- Adjusting the time <-> distance conversion: I aggregated the "5-min" and "10-min" areas into the data zones. I then estimated the number of residents in these two areas by assuming a homogeneous distribution of people in each data zone and using data-zone-level population figures ($Pop = Area \times Density_{Pop}$). The sum across all data zones gave an estimation of the city population contained in the "5-min" and "10-min" areas. It showed that 90% of the population was in the 5-min area and 8% in the 10-min area. It was widely discrepant with the city-wide household data reporting 72% of the population living within 5 minutes of a greenspace and 21% within 10 minutes (*Distance to Green or Blue Space - Scottish Household Survey* n.d.). Proceeding by dichotomy, I adjusted the time <-> distance conversion until it was close to household data (i.e. fell into the confidence interval): a 5 min <-> 250m correspondence was selected, corresponding to 70% of the population for the 5-min area and 25% for the 10-min area.

- Assigning QALY values to estimate the value of the ES per data zone: the 5-min and 10-min areas were assigned their corresponding increase in QALY. A given data zone was then assigned a weighted average of QALY increase - the weights being the areas of each type (5-min or 10-min) overlapping with it.

C.9.3 Limitations

There are a number of sources of uncertainty to the methodology detailed above:

- Determination of the number of active visits to local greenspace in urban areas: the methodology required collating data from surveys conducted in different contexts and asking slightly different questions, which led to a high number of assumptions (see previous section). Furthermore, the applicability of this general data to the specific case of Edinburgh has not been assessed. Local conditions such as greenspace accessibility and quality may influence the estimation provided in this thesis.

- The spatial buffers do not fully reflect the actual walking time to greenspace, according to paths and roads accessible to pedestrians, and the accessibility of greenspace entrances. As a result, the contribution of greenspace to physical activity may be overestimated. I tried to mitigate this uncertainty by ensuring that the proportion of Edinburgh residents living in the different buffers, matched data-zone-specific survey results regarding travel time.

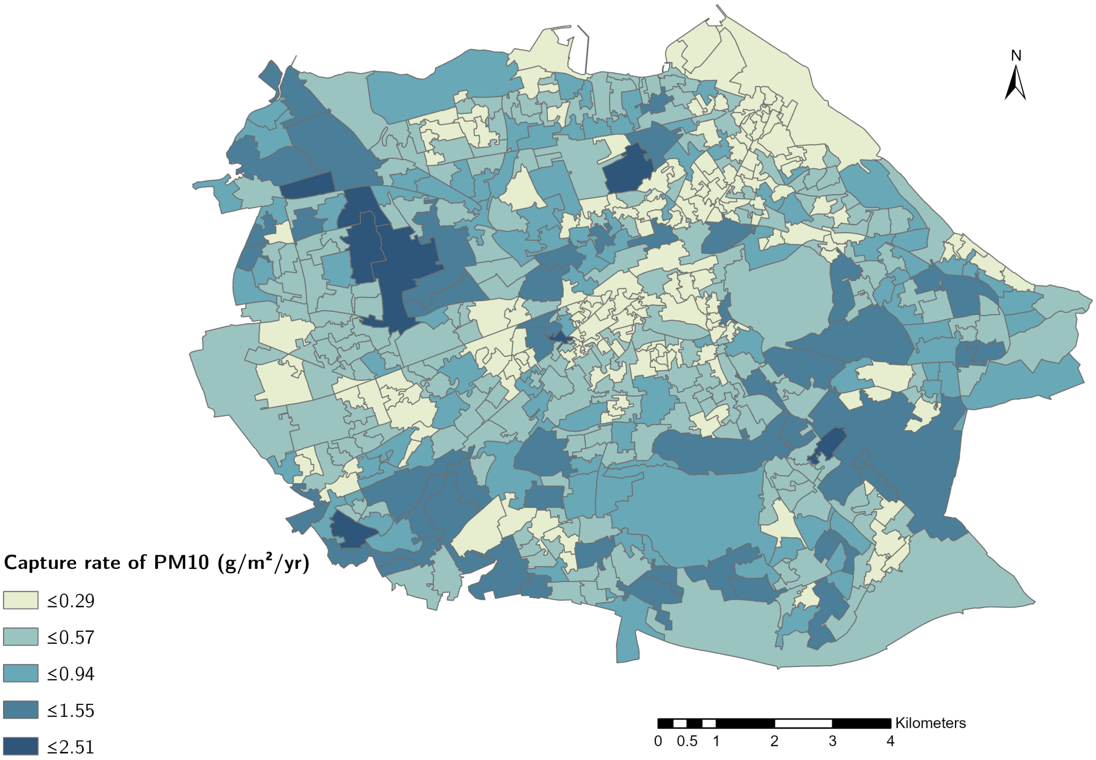
- The confidence interval for the QALY value reported by White et al has not been reported.

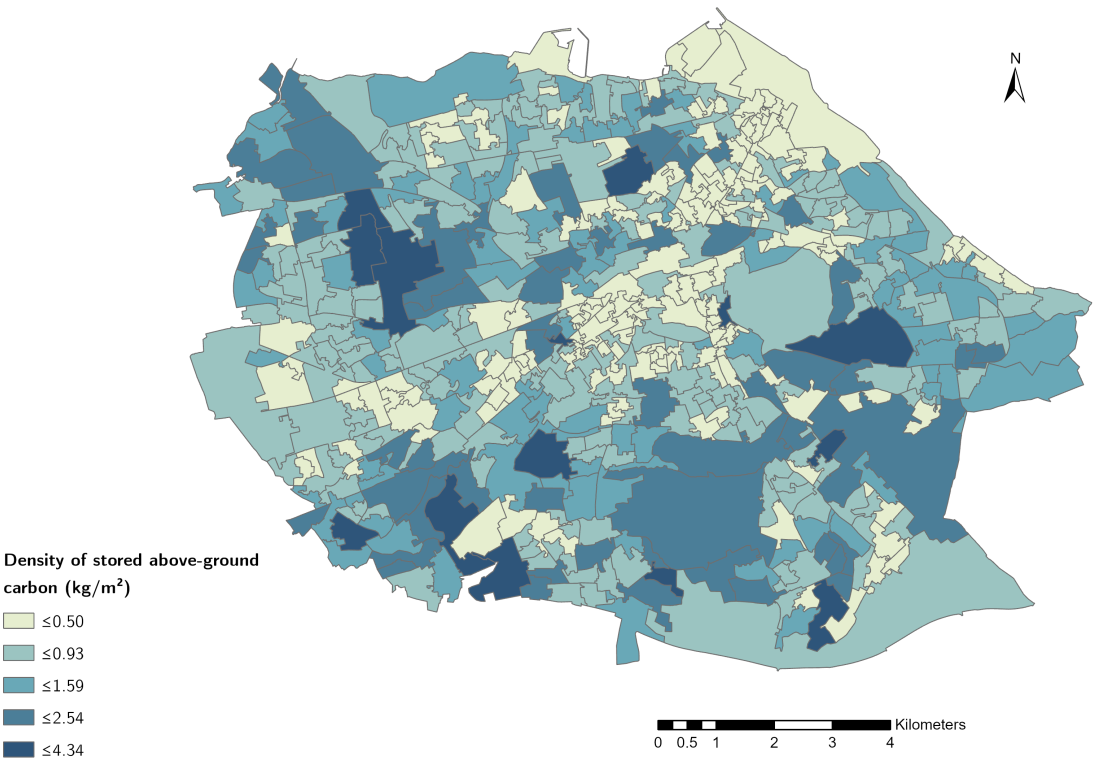
Given the high uncertainty surrounding the methodology, I compared the results of its implementation with similar, but validated, measures of distance to greenspace. The mapping of Fields in Trust showed that all residents were living within 10 minutes of some greenspace (ref), a finding with which results from the implementation of the methodology were consistent. It gave some confidence that the buffering methodology was at least a first approximation of the reality in Edinburgh.

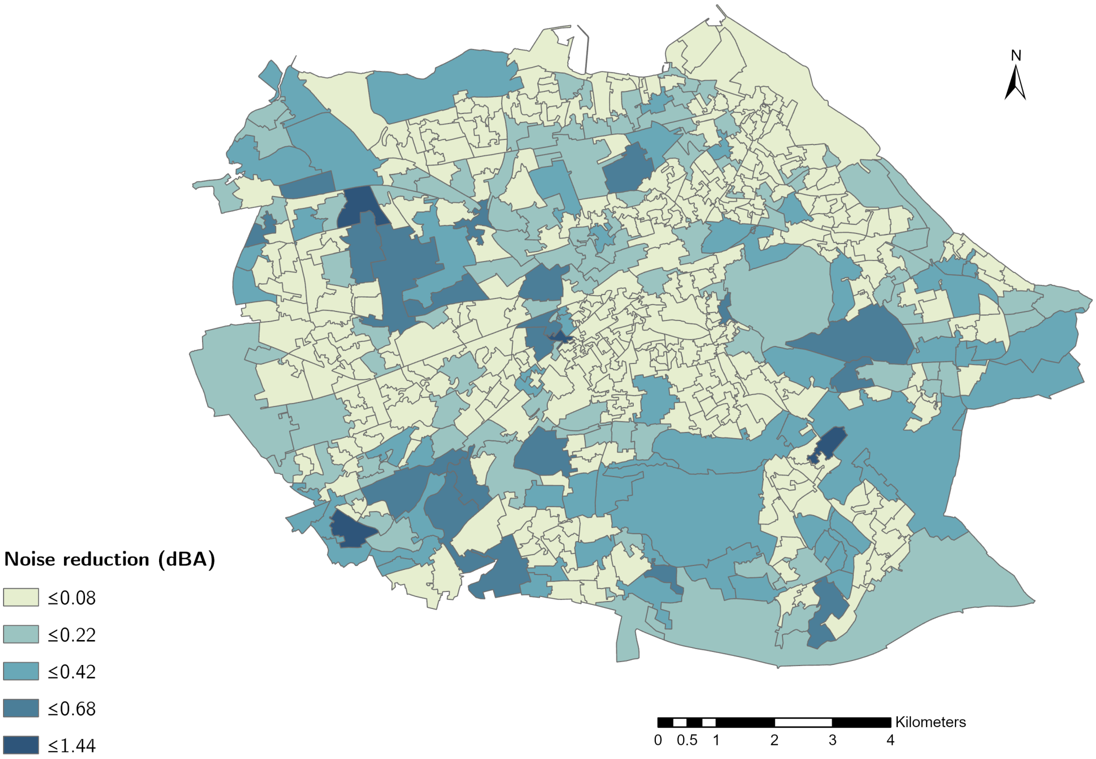
Appendix D

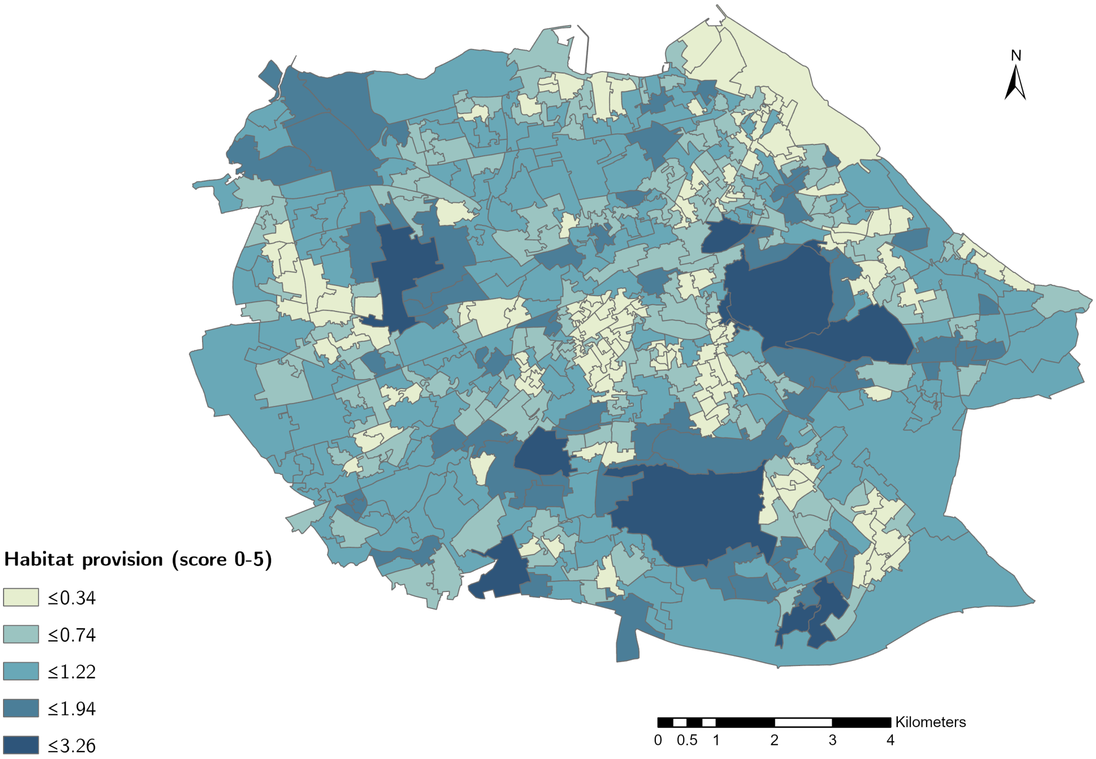
Supporting information on the identification and analysis of bundles in Edinburgh

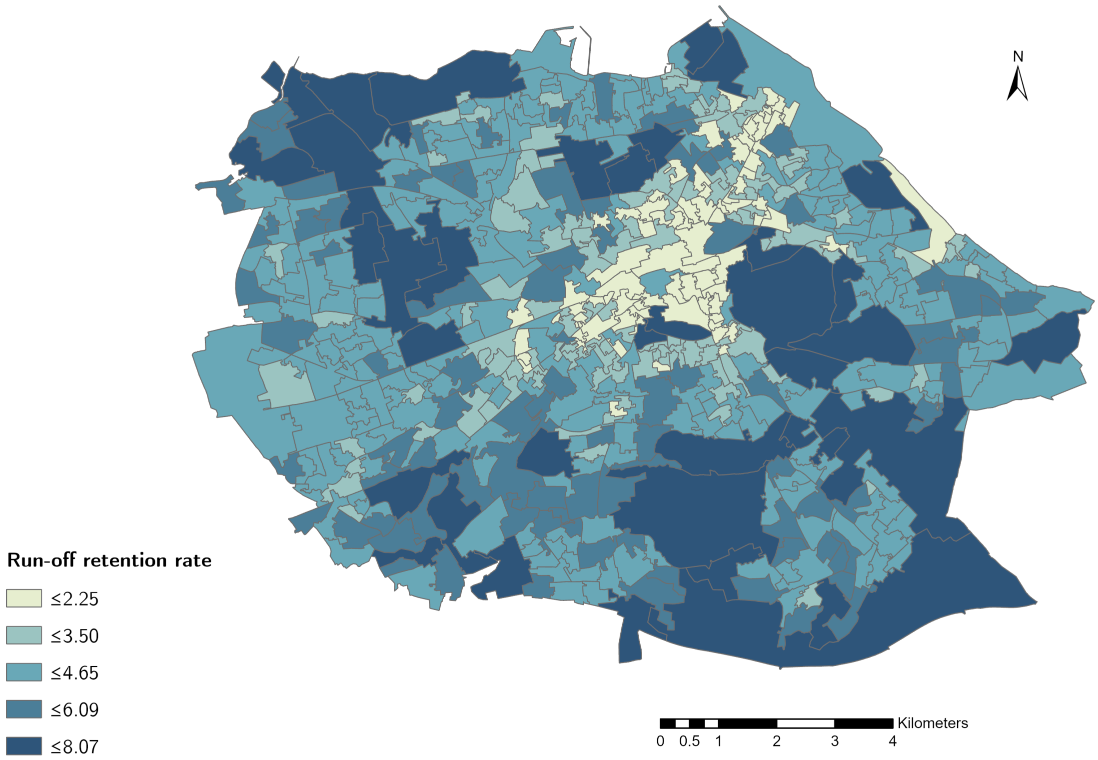
D.1 Individual maps of the selected ES

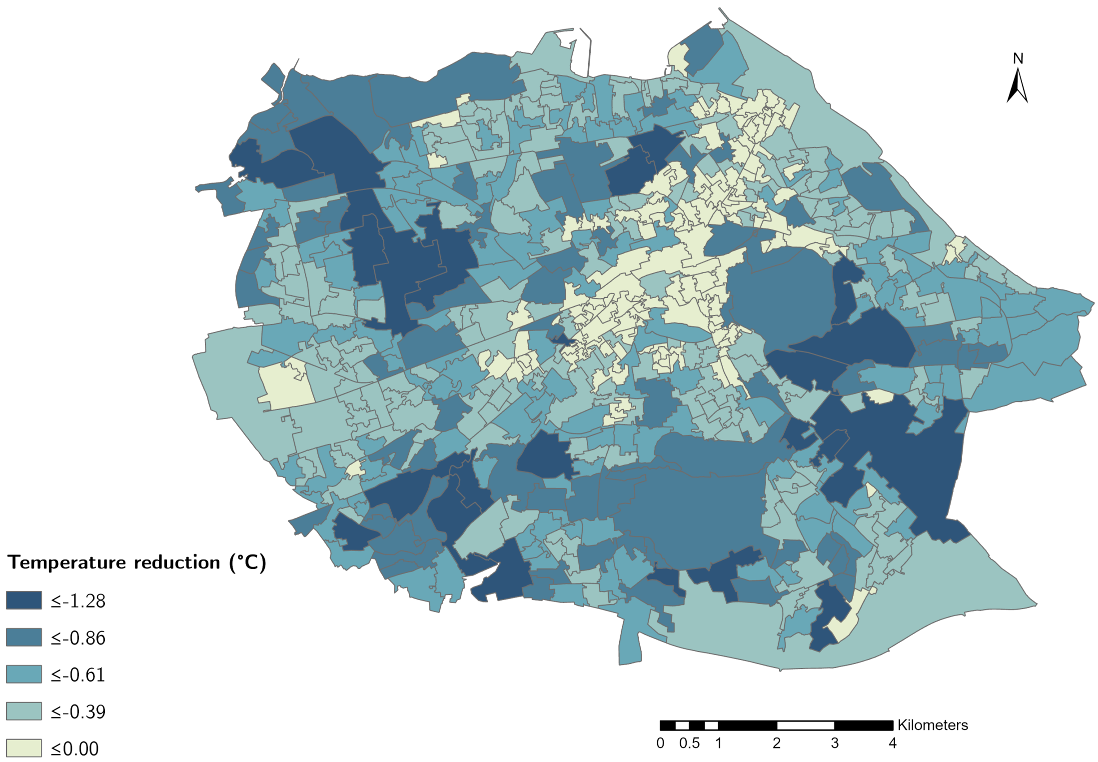


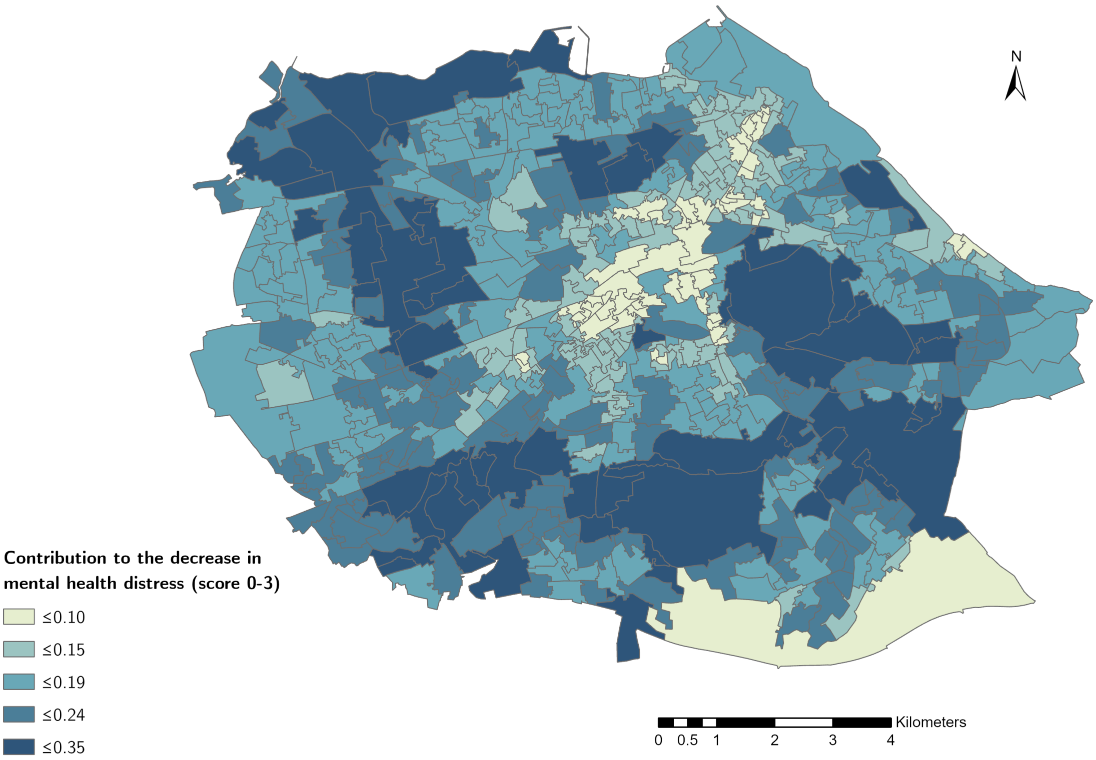


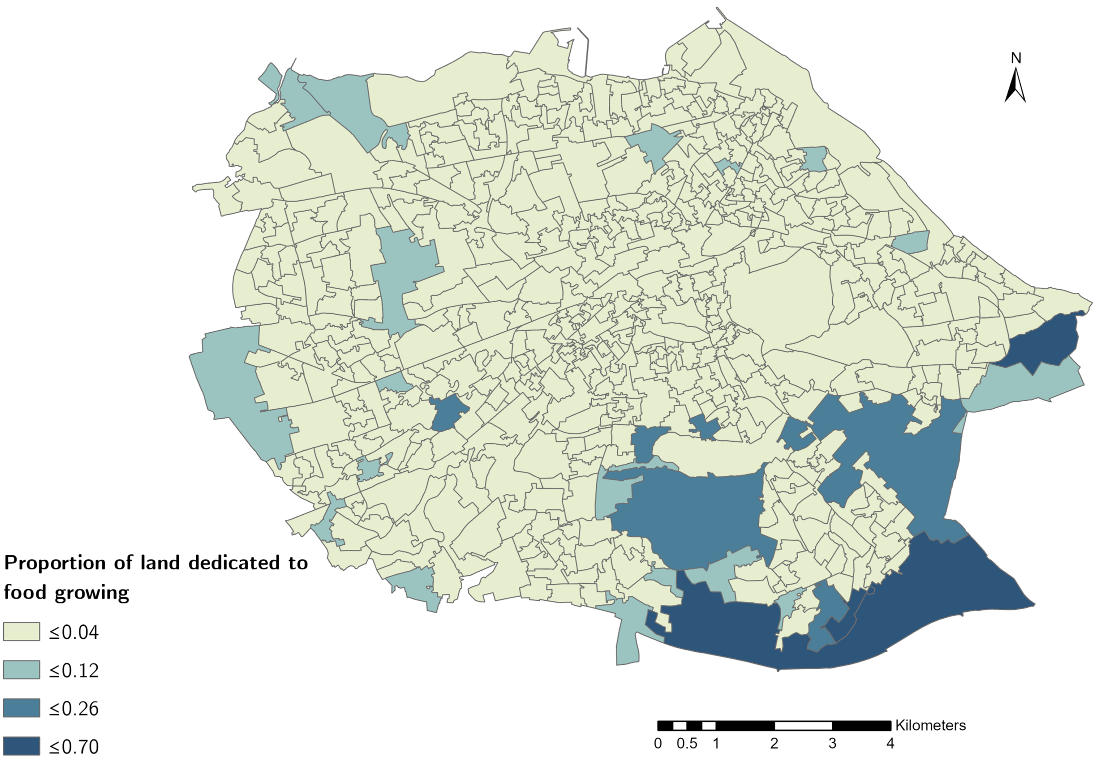

N
Noise reduction (dBA)
≤0.08
≤0.22
≤0.42
≤0.68
≤1.44
Kilometers
0 0.5 1 2 3 4

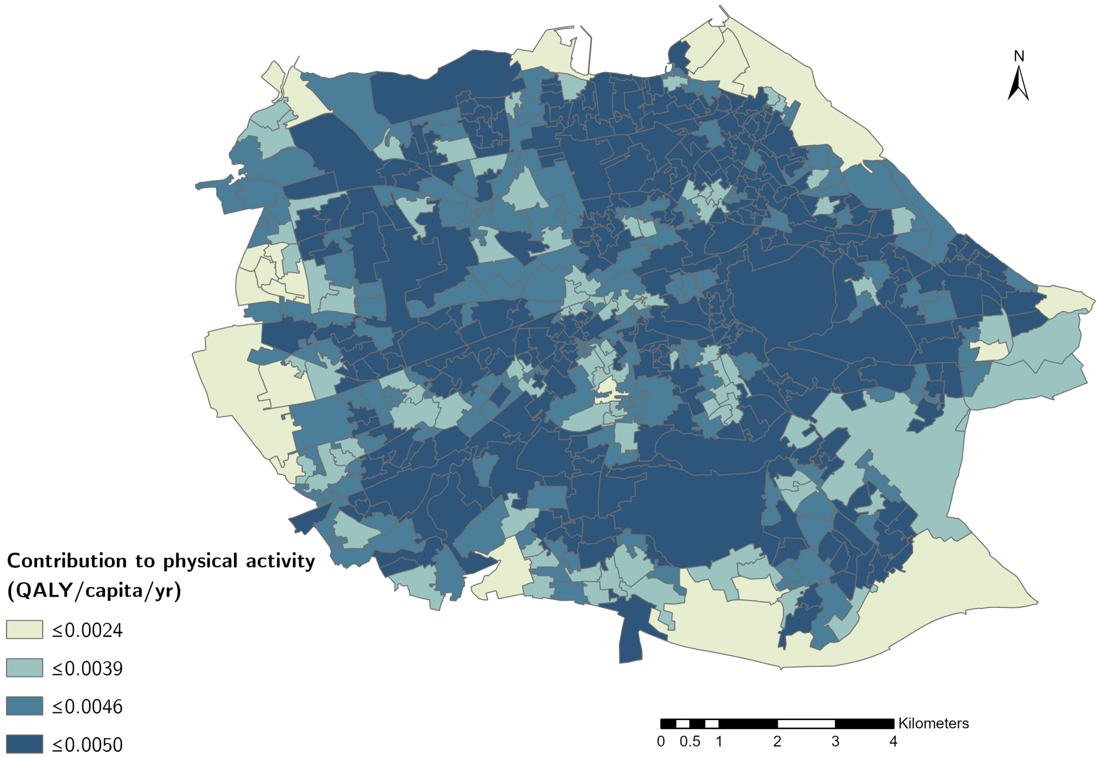

N
Habitat provision (score 0-5)
≤0.34
≤0.74
≤1.22
≤1.94
≤3.26
Kilometers
0 0.5 1 2 3 4


N
Run-off retention rate
≤2.25
≤3.50
≤4.65
≤6.09
≤8.07
0 0.5 1 2 3 4 Kilometers


N
Temperature reduction (°C)
≤-1.28
≤-0.86
≤-0.61
≤-0.39
≤0.00
0 0.5 1 2 3 4 Kilometers


N
Contribution to the decrease in mental health distress (score 0-3)
≤0.10
≤0.15
≤0.19
≤0.24
≤0.35
0 0.5 1 2 3 4 Kilometers


N
Proportion of land dedicated to food growing
≤0.04
≤0.12
≤0.26
≤0.70
0 0.5 1 2 3 4 Kilometers



D.2 Hierarchical analysis for the identification of ES Bundles

Hierarchical clustering was conducted on the first two PCA axes using Ward's minimum variance method. The analysis was implemented in R using the *hclust* function of the core *stats* package. Figure D.1 presents the resulting dendrogram and the height at which the tree was cut.

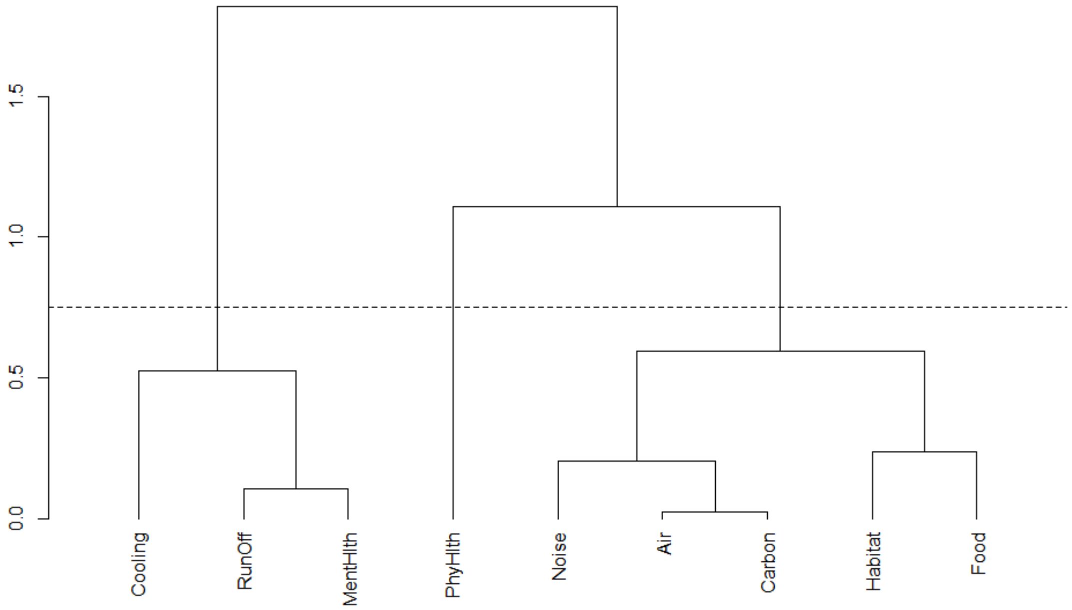


Figure D.1: Dendrogram from the hierarchical clustering performed on the first two axes of the tb-PCA conducted in Chapter 3. The dotted line shows where the tree was cut to identify the clusters.

D.3 Skewness analysis

The skewness γ of a variable X is defined as its third standardised moment:

$$\gamma = E\left[\left(\frac{X-\mu}{\sigma}\right)^3\right]$$

Where E is the expectation operator, μ the mean, σ the standard deviation.

The objective of the skewness analysis was to check whether the ES spatial distributions had a skewness falling within "normal" conditions. First, the skewness range that can be expected from normal distributions of 558 observations was determined, by computing the skewness of 100,000 randomly generated distributions with these characteristics (normal; 558 observations). Then, the skewness of the ES distributions was computed, along with their 95% confidence interval (CI). Any ES with a CI not overlapping with the normal skewness range was deemed to have a skewed distribution.

The methodology was implemented in R using the *Skew* function of the *DescTools* package (Signorell 2019). CIs were computed using the BCa method[1] with 1,000 replicates (directly implemented in the Skew function).

The normal skewness range obtained by setting the seed at the random value of 1512, is:

$$Range = [-0.43, 0.53]$$

The skewness values and confidence intervals of the ES distributions are (Table D.1):

Table D.1: Skewness values and their CIs, for each ES distribution.

	Skewness	CI - lower bound	CI - upper bound
Air purification	1.98	1.60	2.51
Carbon storage	1.94	1.62	2.38
Noise attenuation	3.15	2.37	4.17
Habitat provision	1.03	0.72	1.45
Run-off retention	0.22	0.03	0.40
Temperature regulation	1.24	0.97	1.56
Contrib. mental health	0.24	0.04	0.43
Food growing	10.25	7.78	15.39
Contrib. physical activity	-2.36	-2.74	-2.02

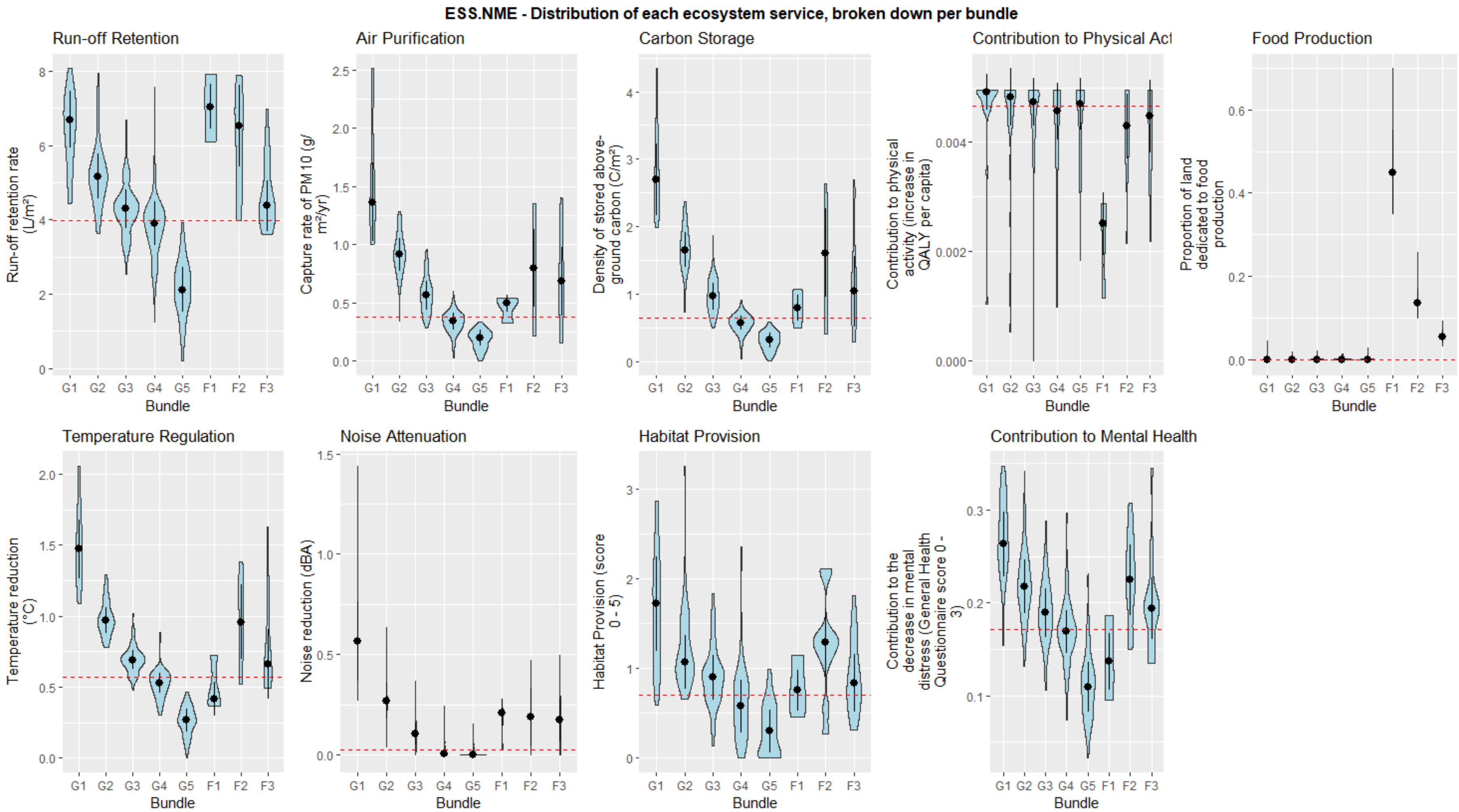
Only run-off retention and contribution to mental health can be deemed not to be

[1]BCa: bias-corrected with acceleration constant

skewed.

D.4 ES distributions in each bundle

The following figure (next page) shows violin plots of all ES for each bundle.


ESS.NME - Distribution of each ecosystem service, broken down per bundle
Run-off Retention
Run-off retention rate (L/m²)
Air Purification
Capture rate of PM10 (g/m²/yr)
Carbon Storage
Density of stored above-ground carbon (C/m²)
Contribution to Physical Act
Contribution to physical activity (increase in QALY per capita)
Food Production
Proportion of land dedicated to food production
Temperature Regulation
Temperature reduction (°C)
Noise Attenuation
Noise reduction (dBA)
Habitat Provision
Habitat Provision (score 0 - 5)
Contribution to Mental Health
Contribution to the decrease in mental distress (General Health Questionnaire score 0 - 3)
G1 G2 G3 G4 G5 F1 F2 F3
Bundle

Appendix E

Supporting information for the study of the integration of the ES concept in decision-making

E.1 Coding schedule

The Excel template for the coding schedule in reproduced in the next two pages.

Decision-making area:	
Document(s) reviewed:	

Component: Ecosystem services			Air purification	Water purification	Carbon storage / sequestration	Cooling	Flood protection / mitigation	Noise attenuation	Pollination	Habitat provision	Recreation	Education	Experiencing nature	Socialising	Supporting identities	Physical activity	Food production	Disservices
	Terms used to refer to ES	Contribution																
		Ecosystem services																
		Benefits																
		Value																
		Phrases linking nature to well-being																
	Mention of specific ES	Air purification																
		Water purification																
		Carbon storage / sequestration																
		Cooling																
		Flood protection / mitigation																
		Noise attenuation																
		Pollination																
		Habitat provision																
		Recreation																
		Education																
		Experiencing nature																
		Socialising																
		Supporting identities																
		Physical activity																
		Food production																
		Disservices																
	Quotes on multiple benefits																	

Component: Nature	Biodiversity		
	Terms used to refer to Nature	Green / Blue spaces	
		Green / Blue infra / network	
		Natural environment / Natural places	
		Natural capital	
		Ecosystem	
	Links between Nature and Ecosystem services	Nature in general	
		Trees / Woodland	
		Water features (rivers, ponds)	
		Soil / Geodiversity	
		Parks	
		Gardens	
		Allotments	
		Brownfields	

Component: Good quality of life			Mentions to ES in general	Mentions to specific ES														
				Air purification	Water purification	Carbon storage / sequestration	Cooling	Flood protection /	Noise attenuation	Pollination	Biodiversity	Recreation	Education	Experiencing nature	Socialising	Supporting identities	Physical activity	Food production	Disservices
	Dimensions mentioned, and their links to ES	Health																	
		Well-being																	
		Sense of place																	
		Energy																	
		Economy																	
	Quotes																		

Component: Anthropogenic assets			Mentions to ES in general	Mentions to specific ES														
				Air purification	Water purification	Carbon storage / sequestration	Cooling	Flood protection / mitigation	Noise attenuation	Pollination	Biodiversity	Recreation	Education	Experiencing nature	Socialising	Supporting identities	Physical activity	Food production	Disservices
	Dimensions mentioned, and their links to ES																		
	Quotes																		

Component: Direct drivers	Drivers and their impact on Nature and ES	Climate change	
		Habitat conversion	
		Pollution	
		Exploitation	
		Invasive species	
		Disease	

Proposed actions / strategic directions			Towards ES	Towards anthropogenic assets	Towards direct drivers
	Types of actions by targetted component	Managing landscape features			
		Building stakeholders' capacity			
		Fostering collaboration			
		Producing or using scientific evidence			
		Providing incentives			
	Quotes	Actions towards ES			
		Actions towards anthropogenic assets			
		Actions towards direct drivers			

E.2 Interview schedule

Section 1: Your position in City government

1.1. Could you state your current position?

1.2. How long have you worked in that position?

1.3. What other positions have you had in the past, either in City government or elsewhere?

1.4. What policies and strategies are you responsible for delivering?

In the next section, we are going to talk about the benefits of urban nature. When I say nature, I mean parks, but also street trees, community gardens, grassland, ponds, rivers, etc. Basically, anything green or blue you can think of.

Section 2: Perception of nature's benefits

2.1. Would you say that urban nature has a role to play in achieving the goals of these policies and strategies? How?

If the interview mentions health and or well-being without talking about the specific contributions (e.g. contact with nature, enhanced physical activity, socialising), the interviewer asks how nature helps with health and well-being.

2.2. The interviewer sums up the key benefits of nature that were mentioned by the interviewee and asks if they got it right. The interviewee may add more details at this point.

2.3. Practically, how are you making sure these benefits are leveraged to move towards achieving the goals of policies and strategies?

2.4. Do you collaborate with other departments to deliver or use benefits from nature? [May be answered in question 2.3] If so, what are the processes?

2.5. The next part of the interview is about a specific terminology called ecosystem services. Have you heard the term before? *[Question is irrelevant if the interviewee has been using the term]*

2.5.1. If so, Section 3; if not, Section 4

Section 3: If the term "ecosystem services" is known

3.1. How would you define ecosystem services?

3.2. In which context have you become familiar with ecosystem services?

3.3. If the ES concept is used explicitly *[we should be able to infer this from the discussion- to ask clearly if not]*:

   3.3.1. What encouraged you to use it?

   3.3.2. What is your experience using it?

3.4. If the ES framework concept is not used explicitly

   3.4.1. Why not? What terminology do you use instead to refer to nature's benefits?

Section 4: If the term "ecosystem services" is not known

Explaining that it refers to the contributions of nature to people we have been talking about. Introduced as a way for people from different backgrounds to be able to collaborate around the idea by using a common language. It has also been adapted into frameworks to classify, measure and ultimately optimise the benefits of nature. (Give examples)

4.1. In your department or in the context of collaborations: do you use a specific terminology to refer to nature's benefits?

4.2. Do you see a use for the ES terminology in your work?

Section 5: Concluding remarks

5.1. Do you think academics can help to operationalise nature's benefits into strategies and action plans?

   5.1.1. If so, how?

   5.1.2. If not, why?

5.2. Do you have anything to add?

E.3 Ethics

The Participation Information Sheet and the Consent form are reproduced in the following pages.

E.3.1 Participation Information Sheet

University of Dundee

Participant Information Sheet

Representation of ecosystem services in urban strategic decision-making

University of Dundee School Research Ethics Committee Approval Number: SREC – UOD-SoSS-GEO-PG-2019-056

You are invited to take part in a research project. Before you decide whether or not you would like to participate it is important that you read the information provided below. This will help you to understand why and how the research is being carried out and what participation will involve. Please let the researcher who gave you this information know if anything is unclear or you have any questions.

Who is conducting the research?

The research is conducted by Nada Saidi as part of a PhD project, under the supervision of Andrew Allan.

Contact details: n.saidi@dundee.ac.uk, a.a.allan@dundee.ac.uk

Who is funding the research?

The research is funded by the University of Dundee and the Scottish Alliance for Geosciences, Environment and Society (SAGES).

What is the purpose of the research?

The research is part of a broader PhD project investigating the problem of simultaneously considering the multiple benefits humans derive from nature, and how that could inform decision-making. The PhD focuses on the case of cities and involves developing a methodology to identify and analyse such multiple benefits. It then aims to investigate how findings from implementing this methodology could be integrated in decision-making, using Edinburgh as an example.

The stakeholder consultation to which you are being invited aims to understand to what extent the idea of (multiple) benefits from nature has permeated urban decision-making in Edinburgh. This will allow to discuss how the multiple benefits analysis developed in the PhD could help decision-makers depending on their perception and integration of the concept. The consultation has three objectives:

1. Understand how strategic decision-makers like yourself view nature's contributions to people and the extent to which they perceive them as part of the solution to current or future challenges.
2. Identify organisational, institutional and political drivers and barriers for the integration of the concept in strategic decision-making
3. Understand how strategic decision-makers like yourself consider the multiple benefits of urban nature, if at all – and if so, how it influences the strategies they frame.

Why have I been invited to take part?

You have been invited to take part because you were identified as having a leadership role in your department in matters related to urban nature.

University of Dundee

Do I have to take part?

No, taking part in voluntary. You may decide to withdraw from the study at any time without explanation, by sending an email to n.saidi@dundee.ac.uk.

What will happen if I take part?

You will be interviewed by the researcher at a time and place of your choosing, following an interview guide with clearly defined questions related to the three abovementioned objectives. The interview is likely to last around 45 minutes and no more than 1 hour.

The researcher will record the interview (if you consent to recording) and take notes.

Are there any risks in taking part?

There are no risks in taking part.

What are the possible benefits of taking part?

There are no direct benefits of taking part. However, by participating to the study you will contribute to furthering knowledge on how to ensure our green spaces provide multiple benefits for humans and the environment. For instance, the study will be used to understand how synergies can be found across different departments for the planning and management of urban nature.

Will my taking part in this project be kept confidential?

Yes. Only the researcher and her supervisor will have access to your personal data. The interview will be anonymised and used as part of a wider analysis, where no specific information will be given that would allow a reader to identify you.

What will happen to the information I provide?

The notes and recording will be stored in electronic format on secure devices. Data will be kept until five years after the end of the PhD project (expected June 2021) and will not be used by anyone other than the researcher.

The results of the research will be published in the researcher's PhD thesis and potentially in a peer-reviewed article. Interview data will be used to discuss the perceptions of decision-makers in general and no specific statements will be attributed to specific participants, or presented in a way that would allow a reader to infer the identity of the participant. In case the results are published as part of an academic article, open-access journals will be preferred.

Should you decide to withdraw from the study, the recording and notes will be destroyed.

Data Protection

The personal data that will be collected and processed in this study are: your name and your role in the City administration (position, responsibilities).

University of Dundee

The University asserts that it lawful for it to process your personal data in this project as the processing is necessary for the performance of a task carried out in the public interest or in the exercise of official authority vested in the controller.

The University of Dundee is the data controller for the personal and/or special categories of personal data processed in this project

The University respects your rights and preferences in relation to your data and if you wish to update, access, erase, or limit the use of your information, please let us know by emailing n.saidi@dundee.ac.uk. Please note that some of your rights may be limited where personal data is processed for research, but we are happy to discuss that with you. If you wish to complain about the use of your information please contact the University's Data Protection Officer in the first instance (email:dataprotection@dundee.ac.uk). You may also wish to contact the Information Commissioner's Office (https://ico.org.uk/).

You can find more information about the ways that personal data is used at the University at: https://www.dundee.ac.uk/information-governance/dataprotection/.

Is there someone else I can complain to?

If you wish to complain about the way the research has been conducted please contact the Convener of the University Research Ethics Committee (https://www.dundee.ac.uk/research/ethics/contacts/).

E.3.2 Consent form

The form is reproduced in the following two pages.

University of Dundee

Informed Consent Template
Version 1, 8th April 2019

Informed Consent for "Representation of ecosystem services in urban strategic decision-making" [1]

	Yes	No
1. Taking part in the study		
I have read the Participant Information Sheet. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time during data collection, without having to give a reason.	☐	☐
I agree to the recording of my interview.	☐	☐
2. Use of the information in the study		
I understand that information I provide will be used to discuss the perceptions of decision-makers in general and no specific statements will be attributed to specific participants, or presented in a way that would allow a reader to infer the identity of the participant. This discussion will be published in the researcher's PhD thesis and potentially in a peer-reviewed article.	☐	☐
I understand that personal information collected about me that can identify me, such as my name or professional role, will not be shared beyond the researcher and her supervisor.	☐	☐
I agree that anonymised direct quotes can be used in research outputs.	☐	☐

[1] This document is adapted from the UK Data Service Template Form April 2018 retrieved from https://www.ukdataservice.ac.uk/manage-data/tools-and-templates.aspx

University of Dundee

Informed Consent Template
Version 1, 8th April 2019

3. Signatures

Participant's Name	Participant's Signature	Date

By signing above, you are indicating that you have read and understood the Participant Information Sheet and that you agree to take part in this research study.

Name of Researcher	Signature of Researcher	Date

4. Study contact details for further information

Nada Saidi: 07 802 620 937 – n.saidi@dundee.ac.uk